The research results described in the following summaries were submitted by the investigators in September 1993 and cover the period from October 1992 through October 1, 1993. These reports include both work performed under contracts administered by the Geological Survey and work by members of the Geological Survey. The report summaries are grouped into the four major goals of the National Earthquake Hazards Reduction Program.

This report has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Parts of it were prepared under contract to the U.S. Geological Survey and the opinions and conclusions expressed herein do not necessarily represent those of the USGS. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

The data and interpretations in these progress reports may be reevaluated by the investigators upon completion of the research. Readers who wish to cite findings described herein should confirm their accuracy with the author.
**Goal I - Understanding what happens at the earthquake source**

Why and how does a segment of a geologic fault suddenly slip and produce an earthquake? What physical conditions within the Earth control where and when an earthquake occurs?

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Goal II - **Evaluating the potential of future earthquakes**

Where are future earthquakes likely? How large will they be? How often will they occur? When will they occur? Where are future earthquakes unlikely?

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Goal III - Predicting the effects of earthquakes

During an earthquake of a certain magnitude, how severely and for how long will the ground shake? Where will hillsides slide, and flatlands fissure and crack? On what types of ground will earthquake damage be concentrated? Which faults will offset the Earth's surface? By how much? Which coastlines will be elevated or submerged? Where will destructive sea waves be generated? What losses to structures are expected?
Goal IV - Using research results

What new hazard reduction strategies become possible as understanding of earthquake phenomena advances? What scientific information is needed and can be furnished to practitioners in the engineering, land-use planning and emergency management communities? How can such information be most effectively communicated to these practitioners?

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Modeling Fault Slip
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INVESTIGATIONS

1. Dynamic shear rupture in a compacting and dilating fault zone at high fluid pressure
2. Dynamic growth of mixed mode shear cracks
3. Fault geometry and earthquake mechanics
4. Modeling geologic deformation rates in the San Francisco Bay region

RESULTS

1. I demonstrated that dynamic earthquake rupture can be modeled using a poro-elastic-plastic constitutive relation in a finite difference calculation.

2. I completed this investigation which I had started some years ago with less adequate computing resources. An idealized crack model was calculated under conditions in which the slip velocity azimuth changes direction during the motion. The azimuth variation depends on the absolute level of shear traction. This suggests the possibility of inverting earthquake records to infer absolute stress.

3. Earthquake mechanics may be determined by the geometry of a fault system. Slip on a fractal branching fault surface can explain (1) regeneration of stress irregularities in an earthquake, (2) stress drop in an earthquake concentrated in asperities, (3) starting and stopping of slip at fault junctions, and (4) self-similar scaling of earthquakes. Slip at fault junctions provides a natural realization of barrier and asperitiy models without appealing to arbitrary variations of fault strength.

4. I wrote a proposal to perform finite element calculations to model long-term geologic slip rates in the San Francisco Bay region. Major strike-slip faults will be prescribed surfaces with a small coefficient of friction. The upper crust will have a Coulomb yield condition with a larger coefficient of friction. Yielding will simulate faulting on unmodeled faults, in particular, dip slip in strike-slip stepovers. The model will be fit to geologic slip rates and can provide an interpolation of those rates.
REPORTS


Regional Seismic Monitoring Along The Wasatch Front Urban Corridor And Adjacent Intermountain Seismic Belt

1434-92-A-0966

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Program Element 1.1

Investigations

This cooperative agreement supports "network operations" associated with the University of Utah’s 92-station telemetered regional seismic network. USGS support focuses on the seismically hazardous Wasatch Front urban corridor of north-central Utah, but also encompasses neighboring areas of the Intermountain Seismic Belt. Primary products for this USGS support are quarterly bulletins and biennial earthquake catalogs.

Results (October 1, 1992 - September 30, 1993)

General accomplishments. During the report period, significant efforts related to:
(1) continued fine tuning of data acquisition software installed in September 1992;
(2) continued upgrading and expansion of the telemetered seismograph network in the Salt Lake Valley, including the installation of four new stations; (3) installation of satellite dishes at USNSN station Dugway and on the roof of the building housing our central-recording lab; (4) cooperative development of software to retrieve USNSN data from the satellite dish; (5) continued upgrading of field equipment at stations that have been operating since the mid-1970s, including improved solar regulators and audio mixers; (6) field testing of a newly designed gain-ranging telemetry system developed by Memphis State University; (7) rerouting of telemetry to a new on-campus node of the State of Utah’s microwave system; (8) implementation of Internet access to information on current local (and worldwide) seismicity via the command "finger quake@eqinfo.seis.utah.edu"; and (9) extended operation of five temporary telemetered stations and one digital seismograph in and around the source area of an $M_L$ 5.8 earthquake which occurred in SW Utah on September 2, 1992.

Network Seismicity. Figure 1 shows the epicenters of 1575 earthquakes ($M_L \leq 4.8$) located in part of the University of Utah study area designated the "Utah region" (lat. 36.75°-42.5°N, long. 108.75°-114.25°W) during the period October 1, 1992 to September 30, 1993. The seismicity sample includes 26 shocks of magnitude 3.0 or greater and 12 felt earthquakes.

The largest earthquake during the report period was a shock of $M_L$ 4.8 on November 4, 1992 (18:22 UTC), located under the Great Salt Lake Desert, NW of the Great Salt Lake. The shock was felt throughout northern Utah, eastern Nevada, and southeastern Idaho. There were no locatable foreshocks, and only nine locatable aftershocks, all of which occurred in the 101 minutes following the main shock. Approximately half of the seismicity detected during the report period was associated with an area of ongoing coal-mining-related seismicity, located within a 60 km radius of Price in east-central Utah (799 shocks, 0.9 $\leq M \leq 3.3$).
Reports and Publications


Figure 1. Earthquakes in the Utah Region, October 1, 1992, through September 30, 1993. Shocks of magnitude 3.0 and larger are plotted as stars, those less than magnitude 3.0 as circles.
The structure controlling most of the tectonics of the Puget Sound region is a sharp bend in the subduction zone, which has forced a pronounced upward arch in the subducting plate. This arch has elevated the over-riding former accretionary wedge to form the Core rocks of the Olympic Mountains and also elevated the older marine volcanic rocks to form the Olympic Peripheral rocks. These Peripheral rocks were underplated at the edge of a much older continent and the Olympic Core rocks may have been underthrust and then underplated to the Peripheral rocks. The presence of relatively deformable meta-sedimentary rocks beneath the igneous Peripheral rocks under the Puget lowland may account for important features of the local tectonics, such as the apparently active basin faults that radiate from the Olympics and the distribution of crustal earthquakes concentrated east of the Olympics near the depth expected for a boundary between the Peripheral and underthrust Core rocks.

Meta-sedimentary rocks of low to medium grade are expected to be much more electrically conductive than volcanic or other crystalline rocks. We are therefore testing the hypothesis of a meta-sedimentary lower crust under the Puget lowland using electromagnetic techniques. We have collected 15 magnetotelluric (MT) sites on an east-west transect along the crest of the Olympic arch from the coast to the Cascades.

The key preliminary result is the observation that the long period phase (about 1000 seconds) of the east-west electric field with respect to the north-south magnetic field is quite low (about 20 degrees) at all the sites along the transect. This polarization involves electric currents that cross the coast from the ocean. The low phase near the coast is a consequence of the fact that currents induced in the ocean flow at a much shallower depth than would be in equilibrium with the structure of the land. This "ocean effect" should dissipate inland as the currents diffuse downwards. The fact that it extends east of Seattle suggests that shallow conductors keep the ocean currents near the surface. However, the outcropping Peripheral rocks form a resistive break that prevents shallow currents in the Olympic Core from crossing to the shallow sediments in the Puget lowland. Thus the very shallow structure is probably not responsible for the large ocean effect inland.

Although three-dimensional complications such as the Strait of Juan de Fuca remain to be examined, two-dimensional forward modeling incorporating the ocean suggests that conductive lower crust beneath the Peripheral rocks in the Puget lowland is a good candidate to explain the observations. We have the capability to directly invert multi-dimensional MT data, but a crucial data gap near the boundary between the the Peripheral rocks and the Olympic core makes such an exercise pointless at this time.

In a second phase of data collection, we are filling in the critical gap in the MT data in the Olympic National Park, re-occupying sites which have insufficient data for high quality long period phases, extending the MT transect east into the pre-Cenozoic Cascades and collecting an array of magnetovariation (MV) sites distributed so as to provide information about the areal distribution of electric current flow. This last step is essential to determine the effects of large scale three-dimensionality on the MT interpretation.
COLLABORATIVE RESEARCH
(TERRA TEK, INC. AND THE UNIVERSITY OF UTAH): Field and Laboratory Study of the Spatial and Temporal Variability in Hydromechanical Properties of an Active Normal Fault Zone, Dixie Valley, Nevada

Award Number 1434-93-G-2280
Program Element 1.1
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Introduction

This report describes a reconnaissance survey of fracturing in the Dixie Valley fault zone, a large normal fault in the Central Nevada Seismic Belt. The spatial distribution, geometry, and intensity of fracturing is described, and fracture permeability is estimated for stress states that may be representative of pre-rupturing and post-rupturing regimes in large normal faults. Finally, we present a preliminary analysis that treats fracture networks as potential reservoirs of high pressure fluid, and consider the effects of injecting this fluid between fault surfaces during the onset of rupturing. This report outlines the results of the first phase in our study of how the permeability structure of a large normal fault might influence the fluid dynamical processes operating during faulting. We are about to begin a series of numerical modeling studies that will provide more comprehensive insight into the role that the internal structure of a fault plays in controlling the fluid pressure buildup and decay associated with earthquake processes.

Dixie Valley Fault Zone

The Dixie Valley fault is located in the Central Nevada Seismic Belt, and last ruptured during a M = 6.8 earthquake in December, 1954 (Slemmons, 1957). The fault cuts and deforms a 25 to 29 Ma old granitic body and overlying Tertiary volcanic rocks along the eastern margin of the Stillwater Mountains (Speed and Armstrong, 1971; Wilden and Speed, 1974). Vertical displacement is estimated as 6 km (Okaya and Thompson, 1985; Parry et al., 1991). Fault surfaces dip 30° to 45° ESE on average, and slickenlines and grooves trend 105° ± 7°. The fault zone is marked by a band of hydrothermal alteration and intense fracturing that is several tens to hundreds of meters wide and extends for tens of kilometers in the footwall adjacent to Quaternary scarps. Locally, the alteration and fracturing extends hundreds of meters into the footwall along narrow zones of intense cross fracturing (Parry et al., 1991).

The slip-zone consists of breccia and cataclasite, together with corrugated fault surfaces, that are preserved at only a few sites within the study area. Transition-zone or 'damage-zone' rock is intensely, but heterogeneously fractured. Fracturing is characterized by three prominent sets: (1) Shear fractures, most of which dip towards the ESE, but some dip WNW. (2) Steeply dipping.
fractures that strike ENE, parallel to the trend of the fault zone. These fractures developed mostly by extension, but many have undergone some shearing. (3) Cross fractures that strike at moderate to high angle to the trend of the fault zone, dip at steep to moderate angle, and form a mixed set of both extensional and sheared fractures. Many fractures in these three sets have undergone multiple stages of hydrothermal alteration, and contain cemented cataclastic grains that were derived by abrasion during fault slip, or injected as a cataclastic slurry during faulting and fluid pressure fluctuations (Parry et al., 1991). Parry et al. (1991) conclude that the hydrothermal mineral assemblages formed as high as 305° C and fluid pressure up to 157 MPa, corresponding to depths of 6 km and nearly lithostatic fluid pressure. Alteration continued during uplift of the footwall by faulting, so that lower temperature and pressure alteration minerals were superimposed on the deeper, higher T and P mineral assemblages. The most important mineral assemblages, in rank from highest to lowest T and P, are (1) biotite - K-feldspar, (2) chlorite + epidote, (3) sericite + kaolinite + smectite, and (4) zeolite + clay.

Field and Computational Techniques

Field Measurements of Fracturing
Fracture intensity and orientation were measured at several sites along the length of the Dixie Valley fault zone. Fracture intensity was measured by counting the number of fractures intersecting a scan-line over a 10 m interval, and averaged at one meter intervals. Several scan-lines were laid out at each site in order to cross fractures at high angle to strike. Photographs were taken of appropriately oriented rock faces at several sites, fracture traces were marked on the photos, and the trace lengths measured (Fig. 1).

Estimates of Permeability
Fluid transport properties of the fractured rock mass are estimated using the model and algorithms of Oda et al. (1987). Permeability tensor \( \mathbf{K} \) is defined by

\[
K_{ij} = \lambda (P_{kk} \delta_{ij} - P_{ij})
\]

\[
P_{ij} = (\Pi/4 \cdot V) \sum_{k=1,N} \left( L_{k}^{2} [a_{k}^{3}] n_{ik} n_{jk} \right)
\]

Fractures are modeled as discs of diameter \( L \). \( L_k \) is the diameter and \( t_k \) is the aperture of the \( k \)th fracture in the model network. \( n_{ik} \) are the three components of the direction cosine of the \( k \)th fracture. \( \delta_{ij} \) is the Kroenecker delta function, and \( V \) is the volume of the fractured rock mass. \( N \) is the number of fractures in the network. \( \lambda \) varies from 1/12 for flow between parallel plates of infinite extent to zero for a non-percolating fracture network. \( \lambda \) is defined as 1/16 (0.064) for calculations in this study, based on the discussion and numerical simulations of Oda et al. (1987).

Fracture aperture (\( t \)) is difficult to assign with any degree of confidence. Aperture decreases rapidly with increasing effective normal stress, and is also a function of the surface roughness and fracture size (Oda et al., 1987). However, none of these functional relationships are well established for fractures at elevated temperature and pressure in natural fault zones. In this study, the initial or 'zero effective stress' aperture (\( t_0 \)) of each fracture is proportional to the fracture diameter, using the ratio (\( t_0/L \)) = 1x10^{-3}. The decrease in aperture caused by effective normal stress is computed using the algorithm and coefficients proposed by Oda (1986).
Figure 1: Fractures traced from a photograph of a rock face in the Dixie Valley fault zone. The view is along strike, and the rock face is perpendicular to the strike of the fault zone.

Implementation of equations (1) and (2) requires simulation of a fracture network based on field measurements of fracture intensity, orientation and trace length. The number of fractures in a rock volume is estimated from the scan-line measurements. The density of fracture poles expressed as % per 1% area on a lower hemisphere stereoplot provides the probability density distribution from which we generate a sample of fractures with the appropriate angular dispersion. Trace length measurements are corrected for sampling bias (Warburton, 1980) and used to assign mean diameters to fractures falling within the orientation ranges of the three prominent fracture sets. Fracture diameters are generated with a negative exponential distribution and the mean diameter specified for each fracture set in Table 1.

The above procedure is automated in a computer program. The code generates an interpolation table of fracture pole orientation density based on field measurements. The operator specifies the total number of fractures to be modeled within a volume of rock, and the mean diameter of fractures in various sets defined by restricted ranges in orientation. A list of fractures is created.
with the appropriate distribution in orientation and diameter. The fracture list (fracture network) is entered into another computer program which implements equations (1) and (2). This latter code computes the initial aperture \((t_0)\) of each fracture as a function of diameter, corrects \(t_0\) for closure caused by the specified stress state, and determines the principal magnitudes and directions of the permeability tensor (Table 2). Oda et al. (1987) provide a thorough discussion and numerical tests of this 'equivalent porous media' algorithm.

**Results**

**Fracture Intensity**

Mesoscopic fracture intensity varies markedly along the length of the fault zone, but fracturing is concentrated in a band up to 300 m wide immediately adjacent to the Quaternary scarps (Fig. 2). Steeply dipping extension fractures strike parallel to the fault zone and occur both as short pinnate fractures originating from fault surfaces (Fig. 4) and as long (meter scale) fractures that truncate several fault surfaces in vertical succession. The scan-line intensity of this latter fracture set is highly variable, but locally exceeds 30/m. Shear fractures, or fault surfaces, mostly dip ESE and intensity varies from 4/m to 10/m. Cross fracture intensity ranges from less than 4/m to almost 30/m, and locally these fractures coalesce into elongate bands of intense fracturing with hydrothermal alteration that extends several hundred meters into the footwall. The cross fractures originate by at least two different processes, 1) local stress concentrations in the wall rock created by spatial variability in slip along corrugated shear surfaces (Fig. 1), and 2) large scale flexing of the footwall during uplift. Microfracturing mimics the mesoscopic fracturing. Thin section study reveals that microfractures are healed and filled with alteration minerals as the result of the same rock-fluid reactions that occurred along mesoscopic fracture surfaces (Parry et al., 1991).

**Fracture Network Model**

A 'generic' fracture network model is created using representative fracture intensity measurements, orientation, and trace length data. The general characteristics of the model are summarized in Table 1, for 1 m³ rock volume. This model is used in subsequent calculations to estimate fracture network permeability and fluid reservoir characteristics. Fracture network heterogeneity is not considered in this preliminary study.

The number of fractures per unit volume \((\rho)\) is estimated from scanline intensity values (eqn. 25, Oda et al., 1987).

\[
\rho <L^2> = \frac{4I_s}{[\pi <\mathbf{n} \cdot \mathbf{q}>]}
\]  

\(<L^2>\) is the mean squared fractured diameter, \(I_s\) is scanline intensity (#/m), and \(<\mathbf{n} \cdot \mathbf{q}>\) is the mean value of the dot product between the poles to fractures in a specific set (defined by unit vectors \(\mathbf{n}\)) and the unit vector parallel to the scanline (\(\mathbf{q}\)). For example, we use histograms of scanline intensity for the three fracture sets to assign average intensities for each set; \(I_s = 8/m\) for both extension and cross fractures (set 1) and (set 3), and 5/m for shear fractures (set 2). Trace length measurements for each set yield in sequence, \(<L> = 0.2\) m (set 1), 0.5 m (set 2) and 0.25 m (set 3) (Table 1). Fracture density is estimated from (3) with \(<\mathbf{n} \cdot \mathbf{q}> = 1.0\). \(\rho_1 = 255/m^3\), \(\rho_2 = 26/m^3\), \(\rho_3 = 164/m^3\), for a total mesoscopic fracture density of 445 fractures/m³. Field and microscopic studies indicate multiple episodes of fracture sealing and filling by hydrothermal
minerals. We account for the possible effects of hydrothermal alteration and cementation by assuming that only 1/3 of these fractures are open and transport fluid at any given time. This proportion of open fractures is only a guess, and is not based on any quantitative information. The real value may be significantly higher, or much lower.

The fluid transport and reservoir properties of fault zone fracture networks are important in theories of rupture initiation and modeling of earthquake precursors (Sibson, 1989; Byerlee, 1993). Most large, normal faulting earthquakes initiate at depth ≥ 10 km. For purposes of modeling we impose stress conditions and fluid pressures that may exist in parts of a normal fault zone at a depth of 10 km, based on studies of fluid inclusions and mineral alteration assemblages (Parry and Bruhn, 1990; Bruhn et al., 1990). In the pre-rupture state, the ratio of fluid pressure (Pf) to lithostatic pressure (PL) is defined as Pf/PL = 0.9. The vertical principal stress (SV) = ρrgz(1-Pf/PL) = 27 MPa, for ρr = 2700 Kg/m³. The major fault surfaces have a coefficient of friction μ = 0.6, no cohesion, and dip 45°. The least principal stress Shmin = 6.8 MPa at failure. For simplicity, we assume that Shmax = Shmin, or

\[ \phi_s = \frac{[Shmax - Shmin]}{[SV - Shmin]} = 0.0 \]  

Fluid pressure presumably drops within the transition-zone either during or after rupturing because permeability increases, and newly formed fractures provide connections to the surface (Sibson, 1989; Parry and Bruhn, 1990; Bruhn et al., 1990). Assume that the post-rupture fluid pressure becomes hydrostatic, that the shear stress is completely relaxed, and the three principal stresses become equal, with a magnitude of 170 MPa. These pre- and post-rupture stress states are chosen to provide upper bounds on fracture volume changes and fluid production from the transition-zone at seismogenic depths.

**Discussion**

Partial closure of fractures between pre- and post-rupture stress states has a marked effect on fracture permeability (Table 2). The maximum and intermediate permeability axes (K1 and K2) plunge more steeply than the plane of the fault zone, and the least principal axis (K3) plunges more gently than the pole to the fault zone in the pre-rupture stress state. The average fracture aperture is 19 microns, and total fracture volume is 0.52 liter. Fracture permeability is large in the pre-rupture state due to low effective normal stress across most fractures. Permeability magnitudes are ≈ 10⁻¹³ m², about 4 orders of magnitude greater than in the post-rupturing stress state (Table 2).

The increase in effective stress between pre- and post-rupture stress states could produce about 0.5 liter of fluid from a cubic meter of fractured, transition-zone rock because of partial closure of fracture apertures. If fluid expulsion occurs during the initial phase of rupturing, this fluid may be injected between fault surfaces and act to trigger an earthquake (Byerlee, 1993). The fluid also acts as a mineralizing agent, carrying ionic species in solution into fractures and voids between fault surfaces, where chemical reactions produce cement and mineral filling that ultimately reduces permeability, and partially heals fault surfaces.
We have collected samples of fault breccias from the Dixie Valley fault that may represent the consequences of fluid migration during fault-related implosion of the host rock. The breccias comprise an ultra-fine grained, buff colored, silicic matrix with angular clasts of what appear to be k-spar rich protolith. Visual inspection of slabbed and sectioned samples reveal that the clasts are matrix supported. Detailed study was accomplished by laser scanning polished slabs and photographs of the breccia cut at a variety of orientations relative to the orientation of the plane of slip. Analysis of the digital images reveals a bimodal distribution of clast sizes with the finer grained clasts generally found along the bounding surfaces of the brecciated pod. If we assume that the ultra-fine grained matrix was precipitated from a fluid at the time of breccia formation then the apparent porosity of the breccia pod, with clasts fully supported by the fluid, is estimated to be about 56%. Further study of the breccia samples may provide insight into the fluid velocities required to fully support the clasts at the time of breccia formation.

Byerlee (1993) proposes a 'fluid compartment' model for fault zones and the triggering of earthquakes. Fluid sealed under high pressure in one compartment is partially drained into an adjacent compartment of initially lower fluid pressure. We use this model to investigate the potential effect of draining fluid from the transition-zone fracture network into the space between opposing walls of faults or 'slip-surfaces'. Assume the following initial conditions at a depth of 10 km: 1) Fluid is initially trapped at hydrostatic pressure in the fault, and 2) fluid is trapped at 0.9 \( P_L \) in the adjacent fracture network. The fault and fracture network are hydraulically isolated until the onset of rupturing, when the seal between the two compartments is broken. Fault permeability is much less than that of the fracture network, and we neglect changes in fluid compressibility during pressure changes.

The final fluid pressure, after equalization of pressure between the two compartments is (Byerlee, 1993):

\[
P_f = \frac{V_{tz}P_{tz} + V_{sz}P_{sz}}{V_{tz} + V_{sz}} \quad (5)
\]

\( V \) and \( P \) are the fracture volumes and initial fluid pressures in the transition-zone (tz) and fault (sz), respectively. We assign \( V_{tz} = 0.52 \times 10^{-3} \text{ m}^3 \), and \( P_{tz} = 0.9 \text{ lithostatic pressure} \) (\( P_{tz} = 243 \text{ MPa} \)) based on the stress and transition-zone structural parameters summarized in Tables 1 and 2.

How large a section of fault surface is affected by injection of fluid from 1 \( \text{m}^3 \) of transition-zone rock? Consider the situation where \( P_f = 171.5 \text{ MPa} \), half the difference between \( P_{tz} \) and \( P_{sz} \).

Rearranging equation 5 to solve for \( V_{sz} \) gives:

\[
V_{sz} = \frac{V_{tz}[P_{tz} + P_f]}{P_f - P_{sz}} \quad (6)
\]

The fault area that can be pressurized from \( P_{sz} = 100 \text{ MPa} \) to \( P_f = 171.5 \text{ MPa} \) is \( V_{sz}/t_{sz} \), where \( t_{sz} \) is the average aperture between opposing walls of the fault. \( t_{sz} \approx 1 \text{ to } 5 \text{ microns} \) for the specified stress conditions according to the joint aperture constitutive law of Oda (1986). A fault surface area \( \geq 100 \text{ m}^2 \) is affected by the fluid injected from 1 \( \text{m}^3 \) of transition-zone rock. This preliminary result is intriguing because fluid from only a small volume of over-pressured rock may apparently reduce the effective normal stress over a large fault surface area. Only small, heterogeneously distributed patches of over-pressured fracture network are required to make the fluid pressure compartment model viable. This conclusion is consistent with observations that the structural and fluid pressure properties of fractured rock are spatially and temporally heterogeneous (Bruhn et al., 1990; Parry and Bruhn, 1990).
Field observations and measurements of fracture networks surrounding large fault surfaces provide important constraints on structural and mechanical properties of large normal fault zones. Large fault surfaces that rupture during earthquakes are encased within intensely fractured rock. The fracture networks provide pathways for fluid flow within the fault zone, and also form fluid reservoirs. High pressure fluid trapped in isolated, fractured-rock reservoirs may bleed into voids between fault surfaces, possibly triggering instability by the reduction of effective normal stress, as envisaged by Byerlee (1993). Estimates of fracture permeability vary from as high as $10^{-13}$ m$^2$ in the modeled pre-rupture stress state, to as low as $10^{-17}$ m$^2$ in the post-rupture state. Our next phase of study involves computing the patterns and rates of fluid flow within fault geometries modeled after our field-based observations.

References


Characterization of Self-Similar Comminution and Slip Localization in Large-Displacement Faults for Application to Laboratory Fault Modelling

1434-92-G-2184

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Program Element I

Investigations

We are conducting a field geologic study of exhumed faults of the San Andreas system to infer the environmental conditions of faulting, the mechanisms of slip, and the physical and mechanical properties of fault zones at seismogenic depths. This type of research will help guide laboratory fault modelling efforts and ultimately will contribute to an understanding of the physics of the earthquake source. Up to this time we have focused our study on the North Branch San Gabriel fault because this fault segment is probably one of the more deeply exhumed and best exposed, large-displacement faults of the San Andreas system. For comparison with the San Gabriel fault, we also have been carrying out reconnaissance studies of other good exposures of brittle faults in the San Gabriel Mountains, e.g., the San Andreas near Wrightwood and Cajon Pass, the Punchbowl fault, and the Sawpit Canyon fault.

Our previous studies of the mesoscopic scale subsidiary fault fabric, mineralogic alteration and fluid/rock interaction, and particle size distributions of the cataclastic fault rocks led us to the conclusion that mature faults of the San Andreas have an internally zoned structure in which the majority of fault slip occurs in a extremely narrow fault core [Chester et al., 1993]. Recent experimental work suggests that friction parameters characterizing rate dependence and slip history effects of friction in gouge layers may scale with the thickness of the actively shearing part of the gouge layer [Marone and Kilgore, 1993; Chester, 1993]. Scaling relations suggest that thicker shearing zones have a larger critical slip distance for the evolution effect of friction, \( D_c \). Increasing \( D_c \) has a stabilizing effect on faults and increases the critical size of the slipping patch necessary to nucleate instability [Marone and Kilgore, 1993; Dieterich, 1986]. In addition, thicker shearing zones decrease the average shear strain rate within fault zones which tends to promote the inherently stable friction mechanism involving solution transfer [Chester, 1993]. To apply laboratory friction relations to crustal faults and to understand the stability characteristics of faults it is important to define the thickness of natural faults. Over the last contract period we have continued our efforts to characterize the internal structure of the San Gabriel fault with the purpose of defining the strain distribution and the active shear zone thickness relevant for scaling laboratory friction relations.

Results

We have characterized deformation intensity along traverses across the San Gabriel fault on the basis of several structural criteria including neomineralization, particle size reduction, microfracture intensity, mesoscopic fracture and veining intensity, subsidiary fault fabric, and reorientation (by shear) of planar fabrics in the protolith. The deformation intensity measured at great distances from the fault core is taken as representing the regional (background) level of deformation characteristic of the protolith. The boundary of the fault zone may be defined where deformation intensity is shown to increase markedly as the fault is approached. The various criteria used to measure deformation intensity imply different thicknesses of the fault zone using this method. All
criteria imply that the regions of intense deformation are relatively localized to a zone within tens of meters from the fault core.

Measurements of mesoscopic fracture, vein and subsidiary fault intensity indicate the protolith has a relatively high background level of deformation with local excursions that are probably associated with lithologic variation and larger subsidiary fault zones (Figure 1a). The increase in mesoscopic fracture, vein and fault intensity associated with the San Gabriel fault occurs within approximately 50 m of the fault core. This is consistent with the characterization of microscopic fracture intensity that suggests a high level of microfracture to at least 30 m from the fault core (Figure 1b). The microfracturing at distances of greater than 10 m from the core and near the boundaries of the fault zone is characterized by dense networks of healed intragranular microfractures. Although the grains (defined on the basis of composition) are severely fractured there is little evidence of shear separation on the fractures. Fracture geometries imply repeated fracture and healing such that the original grains did not lose mechanical integrity over the period of the San Gabriel faulting activity. Extreme comminution with shear displacement along fractures and grain size reduction occurs within a much narrower zone that is within several meters from the fault core (Figure 1c). It is within this narrow zone that evidence exists for extreme alteration and neomineralization (Figure 1d).

Chester et al. [1993] reported that subsidiary fault fabrics within the fault core are different than in the surrounding rock. In general, most fault surfaces and other planar fabrics within the core are oriented parallel to the fault. Outside the core the subsidiary faults are preferentially oriented at high angles to the fault. This observation and the localization of comminution and alteration led Chester et al. [1993] to conclude that the majority of shear strain was accommodated within the fault core. Additional evidence for localization of shear strain to the fault core is provided by measurements of the orientation of granitic dikes along the fault. The dikes are much older than the San Gabriel fault and can be treated as passive markers that record shear strain. Away from the fault the dikes display all orientations including orientations that form large angles with the plane of the San Gabriel fault (Figure 1e). At a distance of less than 5 m from the fault core the dikes display significant and abrupt reorientation subparallel to the fault core. These data constitute strong evidence that significant shear strain occurs only within and near the core of the fault.

The general picture that emerges for the San Gabriel fault zone is that it consists of a wide (approximately 100 m) zone of intense crushing at the microscopic scale but with little net shear. Almost all shear strain has occurred within a central zone on the order of a few meters thick. We have found very similar relations for the other faults studied in reconnaissance. The Sawpit Canyon fault also cuts a protolith containing dikes older than the fault, and the orientations of the dikes clearly record extremely localized shear within a wide zone of crushing.

We have noted previously that the fabric of the fault core suggests that shear displacements are inhomogeneous within the fault core. In most cases there is a layer of ultracataclasite on the order of a decimeter in thickness. This layer is distinct from the surrounding fault-rocks in the core because it displays extreme comminution and nearly complete synfaulting mineralogic alteration [Evans and Chester, 1993]. Furthermore there are localized slip surfaces (slickensides) within and along the boundaries of the ultracataclasite layer. These ubiquitous strain localization features consist of remarkably planar and smooth shear surfaces that are oriented parallel to the fault boundaries and located in the ultracataclastic core of the faults. Some of these surfaces are continuous for distances at least comparable to the thickness of the entire fault zone. At the microscopic scale these surfaces are ~1-mm thick and are defined by preferred alignment of phyllosilicates, juxtaposition of texturally different ultracataclasite, extreme grain size reduction, and mineralized veins along and parallel to the surface. Several structures in the ultracataclasite layer, such as clasts of older ultracataclasite and relatively few large fragments of veins as observed in the less deformed fault core imply that the ultracataclasite layer was periodically reworked during the faulting history [Chester et al., 1993].

Microstructural studies of simulated gouge from friction experiments suggest that gouge structure and frictional behavior evolves with cumulative shear [Marone and Scholz, 1989; Blanpied et al., unpublished manuscript, 1989]. General findings suggest that displacement in gouge layers tends to localize to narrow shear bands and this correlates with a change from rate...
strengthening to rate weakening behavior [Marone et al., 1990]. The extreme comminution within the shear bands can lead to densification and strain hardening such that the shear bands tend to migrate through the gouge layer as slip accumulates. Although only a thin layer is actively shearing at any time, the entire gouge layer is sheared and reworked after large total displacement [Blanpied et al., unpubl. manuscript, 1989]. The structures of the San Gabriel fault core are compatible with such a model. In this case the ultracataclasite layer represents the products of attrition wear along the localized sliding surfaces and shear bands, and the ultracataclasite layer is periodically reworked as the localized shear bands sweep through or jump to new sites within the layer. Reworking also would be expected to occur at locations where the localized shears jog or step within the ultracataclasite layer.

The field relations require that the actively shearing portion of the fault at any increment of time during the fault history must have been much less than the apparent thickness of the fault on the basis of fracture intensity, and must have been equal to or less than the core of the fault that records significant shear strain. This implies that for scaling constitutive parameters such as $D_c$ from simulated gouge friction experiments the thickness of the active shear zone of the San Gabriel fault is a few meters at most but probably much less. The presence of localized shear structures in the core of the fault and evidence for reworking of the ultracataclasite layer imply that deformation in this layer is very similar to the processes in simulated gouge friction experiments. As such, friction parameters such as $D_c$ in the San Gabriel fault may have been very similar to those observed in simulated gouge experiments. Such small $D_c$ values imply that instability can nucleate on localized shear surfaces with lengths similar to those observed in the San Gabriel fault core. Thus we suggest that the localized shear features in the San Gabriel fault could have been the source of paleomicroseismic events or portions of the rupture surfaces of larger paleoearthquakes. Although we argue that the experimental friction parameters may apply for nucleation of instability in the San Gabriel fault, neither simulated gouge experiments nor San Gabriel fault structures indicate if additional and larger $D_c$ values are necessary to describe transient friction for very large slip events.

Reports


Other References


Figure 1. Characterizations of deformation intensity as a function of distance from the ultracataclasite layer in the core of the North Branch San Gabriel fault. a) and b) reflect intensity of brittle deformation associated with the San Gabriel fault whereas c), d), and e) reflect shear strain.

a) Linear density of mesoscopic fractures, faults and veins intercepting two orthogonal scan lines at locations along a traverse across the San Gabriel fault at Bear Creek. Density is generally high near the fault core and lower in the protolith except for local excursions associated with other faults and lithologic variation.
b) Intensity of microfracture in samples from across the San Gabriel fault at three different localities: Pacoima Canyon, Devil's Canyon and Bear Creek. Unfractured rocks have intensity of 0 and rocks with completely demolished grains have an intensity of 100. Intensity is high up to at least 30 m from the ultracataclasite layer. Microfracture intensity was determined from point counts of petrographic sections using an optical microscope. For each grain encountered at evenly distributed points the microfracture density, $d_f$, was determined by counting the number of microfractures within a fixed viewing area and expressed as microfractures per sq. mm. Microfracture intensity is defined by summing the percentage of grains in the following groups, $d_f < 20$, $20 \leq d_f < 120$, $120 \leq d_f < 250$, $250 \leq d_f$, and demolished, multiplied by the factors, 0, .25, .5, .75, and 1, respectively.
c) Volume percent of grains comminuted to diameters less than 10 μm determined from petrographic point counts of samples from traverses across the fault at Bear Creek and Devil's Canyon. Extreme comminution and grain size reduction occurs primarily within a distance of a few meters from the ultracataclasite layer.
d) Volume percent of neomineralized veins, disrupted veins, and porphyroclasts determined from petrographic point counts of the same samples as in c). Most veining occurs within the fault core.
e) Angle between planar fabric elements of the protolith that predate the San Gabriel fault and the San Gabriel fault plane measured in the plane perpendicular to the fault and parallel to the slip direction (horizontal) across the fault at Devil's Canyon and Bear Creek. Significant shear strain is recorded by reorientation of the planar fabric elements only within 5 meters from the ultracataclasite layer.
INVESTIGATIONS

This Cooperative Agreement provides partial support for the joint USGS-Caltech Southern California Seismographic Network. The purpose is to record and analyze data from more than 25,000 local earthquakes from October 1992 to September 1993 and generate a data base of phase data and digital seismograms. The primary product derived from the data base is a joint USGS-Caltech catalog of earthquakes in the southern California region. We also provide rapid response to media and public inquiries about earthquakes.

For more detailed information about data access, please contact:
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RESULTS

Network Operation

Southern California Seismographic Network. The SCSN has 250 remote sites (with 330 components) and gathers data from local, regional and teleseismic earthquakes. These data are used for earthquake hazards reduction as well as for basic scientific research. The earthquake hazards reduction effort has become more important as moderate-sized earthquakes continue to occur within densely populated areas in southern California. The largest damaging earthquake to occur was the (M_w=6.2) Eureka Valley earthquake of 17 May 1993, located near the California Nevada state boundary.

The average rate of 15 publications per year over the last 10 years using the network data illustrates the strength of the ongoing research activities that use the network data. Continued efforts to improve data quality and accessibility have created the arguably best regional earthquake data base in the world. The ongoing upgrading of the quality of the waveforms recorded by the short-period network and the addition of low-gain seismometers and accelerometers provide numerous new avenues of research. Most important of these is analysis of on-scale waveforms to determine source, path and site effects.

The USGS operates most of the remote stations in the SCSN. Caltech operates: 1) 24 short period telemetered stations; 2) 12 very broadband TERRAscope stations; in 1994 we plan to install 7 more TERRAscope stations. Caltech also maintains drum recorders and other equipment at the central site located in the Seismological Laboratory at Caltech.

The SCSN data are recorded by two microVAX-III computers and the data processing is done on six VAX workstations using a VAX-4000 as a central server. The operation of this equipment is shared by Caltech and USGS personnel. To avoid duplication, software development is done in cooperation with the USGS in Menlo Park.
More than 25,000 earthquakes will be entered into the southern California earthquake catalog for this reporting period. Approximately 5.0-10.0 Mbytes of phase data and 50-75 Gbytes of seismograms will be archived. In addition to the data analysis we carry out software maintenance, hardware maintenance and other tasks necessary to complete the catalog. Caltech and USGS maintain a data base that includes: 1) earthquake catalog (1932-present); 2) phase data (1932-present); 3) photographic paper seismograms (1930-1992); and 4) digital seismograms (1977-present). The earthquake catalog (1932-present) and phase data (1932-present) are available via dial-up and over INTERNET. Other data are available upon request. This data base has been made available to the DC/SCEC and is the most voluminous part of the data stored in the DC/SCEC.

Near real-time reporting to USGS in Reston and the Governor's Office of Emergency Services and other response to any felt or damaging earthquake activity is provided by network personnel.

The Data Center of the Southern California Earthquake Center. This center has significantly increased the use of the data from SCSN for scientific research. The mass-store system, which became operational on 1 October 1991, provides on-line storage for more than 300 Gbytes of data. The availability of 60 years of catalog, 60 years of phase data, and 15 years of digital seismograms on both UNIX and VMS computers and on-line over INTERNET/NSFNET improves the access to the data.

Seismicity October 1992 - September 1993

The Southern California Seismographic Network (SCSN) recorded approximately 25,000 earthquakes during the 12 months from October 1992 through September 1993, an average of 2000 per month, making it the second most active reporting period ever (Figure 1). The largest earthquake to occur was the M6.2 Eureka Valley earthquake. Four earthquakes of 5.0<M<6.0 occurred during the last 12 months. Three of these were Landers aftershocks, while one occurred near Bakersfield (Figure 2).

The (M_w 6.2, 7.4, 6.3) 1992 Landers sequence that began on 23 April with the M_w 6.2 1992 Joshua Tree preshock is the most substantial earthquake sequence to occur in the last 40 years in California. These earthquakes ruptured almost 100 km of both surficial and concealed faults and caused aftershocks over a 100 km wide and 180 km long area. The faulting was predominantly strike-slip and all three events had unilateral rupture to the north away from the San Andreas fault. The aftershocks from these earthquakes that have continued through 1993 form several prominent trends in the San Bernardino and western Mojave regions.

Other regions of high activity are the San Jacinto fault, the most active fault in southern California, Coso geothermal area, Eureka Valley, and Long Valley. The activity along the San Jacinto fault extended more than 100 km south of the US Mexico border. The Coso seismicity has remained at a high level since the 28 June Landers earthquake. This high rate of seismicity is anomalous for southern California when compared with the previous decade (Figure 2).

PUBLICATIONS USING NETWORK DATA (ABSTRACTS EXCEPTED)


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Figure 1. Number of earthquakes recorded and processed per year by the Southern California Seismographic Network. Some data from the late 1970s and early 1980s and from 1992 still remain to be processed.
Figure 2. Map of epicenters of earthquakes in the southern California region, 1 October 1992 to 30 September 1993.
Washington Regional Seismograph Network Operations

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Program Element 1

Investigations

Operation of the Washington Regional Seismograph Network (WRSN) and preliminary analysis of earthquakes in Washington and Northern Oregon continue under these contracts. Quarterly bulletins which provide operational details and descriptions of seismic activity in Washington and Northern Oregon are available from 1984 through the third quarter of 1991. Final published catalogs are available from 1970, when the network began operation, though 1986.

The University of Washington operates 94 stations west of 120°W under this agreement. This report includes a brief summary of significant seismic activity. Additional details are included in our Quarterly bulletins.

Network Operations and Outreach

Station WPO, in west Portland, OR, was reinstalled (on 4/15/93) at the same site where it previously operated between 1986 and 1988. WPO replaced station WP2, which operated from late 1988 through Oct. '92. A new station (RCM) using a 1.72 Hz Ranger seismometer was installed at Camp Muir on Mt. Rainier in September in order to allow us to more accurately locate earthquakes and icequakes on the volcanic cone. Camp Muir was selected because it is high on the mountain and can be readily accessed. Because of earthquake activity in the Klamath Falls, OR area, four new stations were installed in early October by the USGS and telemetered to the UW. These stations are HAM (Hamaker Mt.), LAB (Little Aspen Butte), VSP (Spence Mtn.), and VRC (Rainbow Creek). LAB is a three-component short-period station with an additional high-gain vertical component. A station map and a discussion of new broadband instrumentation is included in the summary for agreement 1434-92-G-2195.

For significant local events, our automatic processing includes an alarm that initiates electronic mail or faxes to local emergency response agencies, operators of adjacent seismograph networks, and the National Earthquake Information Center in Colorado. When the event has been fully processed, updated final information on it is also faxed or e-mailed. A taped message on our voice mail system (206) 543-7010 gives information on felt earthquakes in the last few days within our network, and a longer general message is available on earthquakes in the Pacific Northwest. In addition, locations of recent significant earthquakes can be obtained via modem by dialing (206)685-0889 and logging in as "quake" with password "quake", or via ethernet using the UNIX utility "finger quake@geophys.washington.edu".

Summary cards for all earthquakes located by the WRSN since 1969 are available via anonymous ftp on "geophys.washington.edu" in the pub/seis_net subdirectory. In addition, special sub-directories; pub/kfalls and pub/woodburn; include locations, focal mechanisms, and local station lists for the Klamath Falls and Scotts Mills, Oregon earthquake sequences.

We answer from 5-40 questions per day on Pacific Northwest seismicity and seismic hazards, and give about a half-dozen lab tours or presentations each month for a wide variety of age groups; students from elementary through post-graduate, retirees, science teachers, emergency educators, etc. Requests for information increased after the Scotts Mills and Klamath Falls earthquakes in Oregon in March and September, respectively.
Seismicity

Two damaging earthquake sequences occurred in Oregon during this reporting period. Both were unusual because they occurred in areas where damaging seismicity was unknown historically. These sequences, near Scotts Mills (beginning in March, 1993) and Klamath Falls (beginning is September, 1993), are discussed below.

The Washington Regional Seismograph Network processed 3,126 events between Oct. 1, 1992 and Sept. 30, 1993. Of these 2,425 were earthquakes or blasts within the network and the remaining events were either regional earthquakes (156), teleseisms (545), or events too small to be located.

Figure 1 shows earthquakes ($M_c \geq 2.0$) located in Washington and Oregon during this reporting period. Excluding blasts, probable blasts, and earthquakes outside the U. W. network, a total of 1,572 earthquakes west of 120.5°W were located between Oct. 1, 1992 and Sept 30, 1993. Of these, 373 were located near Mount St. Helens, which has not erupted since October of 1986. East of 120.5°W, 174 earthquakes were located.

During this reporting period there were 32 earthquakes reported felt west of the Cascades, and 1 reported felt east of the Cascades.

The Scotts Mills, Oregon Earthquake Sequence

A damaging $M_L 5.7$ ($M_c 5.6$) earthquake occurred about 20 km SE of Woodburn, OR on March 25 at 13:34 GMT. The closest town to this earthquake was Scotts Mills, OR and is known as the Scotts Mills sequence. Figure 2 shows a map view and two cross sections of the best-located earthquakes from the Scotts Mills sequence. These earthquakes were relocated by Thomas et. al. (1993) using additional readings from portable stations deployed by the USGS following the mainshock. The earthquakes are at depths of 7-15 km, and lie in a plane which strikes N75W and dips steeply to the NNE. The focal mechanism of the main shock (also shown in Fig. 2) is compatible with this interpretation.

Damage was reported in the Polk, Washington, Clackamas, Marion, and Yamhill counties of Oregon. Notable damage (according to the Portland Oregonian) included: cracking of the Oregon state capitol rotunda and shifting of the "Oregon Pioneer" statue on the rotunda tower in Salem; extensive damage to St. Mary’s Catholic Church in Mount Angel ($4 million to $6 million) where bricks fell from 200 foot tower and walls separated from the roof; a 6 inch drop of the roadway on the Yamhill River bridge River on Oregon 18 near Dayton because of the failure of rocker bearings; damage to the Molalla Union High School south campus ($2 million) where bricks covering gables at the south end of the building fell, blocking the door; and structural damage to the Forest Grove Fire Hall in Washington County and to the Salud Medical Center in Woodburn. The USGS Preliminary Determination of Epicenters (12-93) lists Modified Mercalli Intensities for many communities, and a preliminary intensity map appeared in an article entitled "March 25, 1993, Scotts Mills earthquake - western Oregon’s wake-up call" by Madin, Priest, Mabey, Malone, Yelin and Meier, Oregon Geology, Vol. 55, No. 3 (May, 1993). The mainshock was felt widely around Portland and to the south of Portland, and was reported (in the Oregonian) to be felt from Seattle, WA to Roseburg OR.

The Klamath Falls, Oregon Earthquake Sequence

Beginning on September 21, a highly unusual sequence of earthquakes occurred near Klamath Falls, Oregon in an area which normally has no detectable seismicity. The 1993 Klamath Falls earthquake sequence includes two events ($M_c 5.9$ and 6.0) on September 21 that are among the largest earthquakes to have occurred in Oregon in this century (the felt area of the 1936 Oregon/Washington border earthquake was larger). This sequence included a felt foreshock, the two mainshocks, and many aftershocks. The initial foreshock, $M_c 3.9$, was felt in the Klamath Falls area at 03:16:55 GMT; followed twelve minutes later by the $M_c 5.9$ earthquake at 03:28:55 GMT. Sixteen aftershocks in the $M_c$ 2.4-3.8 range (including two felt $M_c$ 3.8 earthquakes at 04:16 and 04:34 GMT) were then recorded prior to the second mainshock ($M_c 6.0$) at 15:45 GMT. A total of
106 earthquakes $M_c$ 1.7 and larger located in the area by the end of September, and aftershock activity continued in October. A preliminary report on this sequence was published in Oregon Geology (Wiley et al., 1993).

Figure 3 is an epicentral plot showing the best-located earthquakes in the Klamath Falls area. Because the Klamath Falls area lies between the areas covered by the WRSN and CALNET, A.I. Qamar (UW) and K. Meagher (USGS) have recomputed locations by combining WRSN and CALNET data and using data from portable instruments placed in the epicentral region the day after the main shock. They used a velocity model based on the Modoc Plateau (Zucca et al., 1986, JGR, V. 9, pp. 7359-7382). Station corrections were determined using travel-time residuals from three well-located aftershocks for which arrival-time readings were available from close-in portable stations.

The earthquake hypocenters occurred in several groups that were initially isolated from one another. For example, the $M_c$ 6.0 earthquake occurred in a cluster 5 km northwest of the cluster that included the earlier $M_c$ 5.9 earthquake. Fault plane solutions indicate that both main shocks were normal faulting on north to northwest trending faults; one interpretation is that both earthquakes lie on different segments of the same fault zone. Two days after the main shocks another fault zone became active near the western shore of Klamath Lake in an area that is 8 km east of the primary fault zone. Unlike the primary fault zone which had earthquakes with foci up to 12 km deep, the earthquakes along the western shore of Klamath Lake were very shallow.

Geologically, the Klamath Falls area lies at the westernmost extent of the Basin and Range geomorphic province, and the current activity is along the western margin of the Klamath Graben; in a down-dropped area bounded by normal faults. Focal mechanisms of both main shocks correspond to normal faulting along northwest striking faults. In 1968 another basin and range sequence occurred in southern Oregon in the Warner Valley near Adel, OR. Reports from geologists who examined the Klamath Falls area after the earthquakes indicate that although cracking due to settling of unconsolidated material was observed, no evidence of primary ground rupture was found.

Two deaths, one due to a rockfall triggered by the earthquake, and another from a heart attack were attributed to the earthquakes. Damage was severe in the Klamath County Courthouse, a hybrid building with several additions. Other notable damage included cracking of a highway bridge over a canal on state Rt. 140 (probably due to settling), broken or cracked parapets in brick buildings, fourteen broken display windows at "Yesterday's Plaza" antique mall, and damage to the Oregon Institute of Technology student union building (a modern building with an eccentric floor plan). Many homes were also damaged, particularly masonry chimneys and veneer. This earthquake was located in a rural area where historic seismic activity was unknown. Based on geologic similarity to areas to the east and south where seismic activity has occurred, Klamath County was in the very earliest stages of developing emergency plans for earthquakes. Plans for rural areas must consider problems such as dispersed population, sparse emergency resources, and a lack of trained personnel to conduct building inspections. Aftershock activity has continued into October.

Reports and Articles
Univ. of Wash. Geophysics Program, 1993, Quarterly Network Report 92-D on Seismicity of Washington and Northern Oregon
Univ. of Wash. Geophysics Program, 1993, Quarterly Network Report 93-A on Seismicity of Washington and Northern Oregon
Univ. of Wash. Geophysics Program, 1993, Quarterly Network Report 93-B on Seismicity of Washington and Northern Oregon
Univ. of Wash. Geophysics Program, 1993, Quarterly Network Report 93-C on Seismicity of Washington and Western Oregon


Abstracts
Qamar, A.I., and K.L. Meagher , 1993, The 1993 Klamath Falls, Oregon Earthquake Sequence, Special Session, Fall 1993 AGU meeting
Figure 1. Earthquakes larger than magnitude 2.0 between Oct. 1, 1992 and Sept. 30, 1993. Locations of a few cities are shown as white-filled diamonds. Earthquakes are indicated by filled symbols, where the round symbols represent earthquakes at depths shallower than 30 km, and squares represent earthquakes at 30 km or deeper. Small "x" symbols indicate locations of seismometers operated by the WRSN at the end of Sept. 1993 and shaded triangles show the position of Cascade Volcanos. See the report on 1434-92-G-2195 for more information on stations.
Figure 2. Map view and cross sections of best-located earthquakes (shown as circles) from the Scotts Mills sequence (3/25/93 mainshock $M_c$ 5.6); located with a modified version of our Puget Sound velocity model, $M_c \geq 0.9$, $\geq 6$ P arrivals, $\geq 3$ stations with both P and S readings, and azimuthal gap < 180°. Positions of temporary stations operated by the USGS are shown by triangles. Cross-section orientations are shown on the map by dashed lines; azimuths and end-point coordinates are indicated on the sections. The main shock focal mechanism shock is shown as a lower-hemisphere, equal area projection - see Fig. 3 for key to focal mechanisms.
Figure 3. Best locations for earthquakes in the Klamath Falls, OR area; third quarter, 1993. The two largest earthquakes (shaded circles) were on 9/21/93 at 03:28 (M = 5.9) and 04:45 (M = 6.0) UT. All locations contain arrival times from both CALNET (USGS, Menlo Park) and WRSN (UW, Seattle). Seismograph stations are shown as triangles. Most stations were portables deployed after the mainshocks. Permanent stations VSP, VRC, LAB and HAM (bold) were installed by the USGS in early Oct. Readings from portable stations are used for some aftershocks. Faults shown are from the dissertation of Silvio Pezzopane, U. of Oregon. The normal focal mechanism (lower hemisphere, equal area) for the first mainshock was determined from combined UW and CALNET polarities. The mechanism of the second mainshock is similar.
The New England Seismic Network

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Network Status

Weston Observatory was operating 23 seismic stations spread throughout New England through September 30, 1993, and in addition MIT was operating 9 seismic stations in New Hampshire and Massachusetts during this same time period. Nineteen of the Weston Observatory NESN remote seismic stations were single-component (vertical) stations (1 Hz velocity transducer geophones) linked via analog telephone telemetry to Weston Observatory where event triggering and recording is being done on a PC computer. The three other remote stations (at Moodus, CT, Gaza, NH and Milo, ME) are new PC-based stations, with digitizing and event triggering at the remote site and data telemetry via dial-up telephone connections. All three of these stations have three-component 1-Hz force-balanced sensors which are somewhat broader band than the standard velocity transducer. During the fall of 1993 Weston Observatory began to purchase the equipment for 15 new PC-based stations to replace the analog stations which lost their telemetry on October 1, 1993. Each of these new stations, to be operated jointly by Weston Observatory and by MIT, will be comprised of a three-component set of broad-band sensors.
(peak sensitivity in the 30 sec to .03 sec period range), a 16-bit A/D system, a PC capable of recording both individually triggered events and 7-days continuous data, and a modem for dial-up telephone telemetry to the central recording sites (Weston Observatory and the Earth Resources Laboratory at MIT). Initial deliveries and testing of the new equipment is being conducted during the fall of 1993 and winter of 1994, with the first station installations expected to be complete by the spring of 1994. The total coverage of these new PC stations combined with that of the U.S. National Seismic Network (USNSN) stations will be equivalent to that operating in New England prior to 1993.

Weston Observatory and MIT continue to archive independently the waveform data for the seismic stations which they have operated. However, each institution now has the capability to convert these waveforms to SAC format for external distribution, and ftp accounts are available at each institution for easy external access to the waveforms as well as the event location data. For the Weston Observatory data, both location files (with .XX extensions) and station waveforms in SAC format (the file name prefixes are the date, day of year and time of the record and the extension is the station name), one connects via ftp to BCINFO.BC.EDU, username: ANONYMOUS, password: GUEST. The files are in a subdirectory named [FTP.EBEL].

There are now 4 USNSN stations in New England in addition to the Weston Observatory/MIT regional network stations. A USNSN satellite receiver has been installed atop Weston Observatory, and it will be made operational to receive the USNSN data during early 1994. Weston Observatory will act as a regional node with the capability of receiving and transmitting USNSN data.

Seismicity

Figure 1 shows the local and regional earthquakes recorded by Weston Observatory from October 1, 1992 to September 30, 1993. A total of 29 local earthquakes from New England and vicinity with magnitudes from 1.6 to 4.0 were detected and located by the network, five of which were felt. In addition to these events, a number of microearthquakes and suspected events, too small to be located, were detected by the network. Significant earthquakes during this time period included a $m_{Lg}(f)=3.4$ earthquake at Franklin, NH on October 6, 1992 which was felt throughout central New Hampshire. A small earthquake ($m_{Lg}(f)=1.7$) was felt by a few people at Littleton, MA, while a $m_{Lg}(f)=2.7$ event was widely felt south of Boston on July 28, 1993. Perhaps most significant in the
seismicity was that a total of 6 earthquakes were detected and located in northeastern Massachusetts during this reporting period. The earthquakes were spread along the trend of the Clinton-Newbury and Bloody-Bluff fault systems in Massachusetts, suggesting that there may be an association between the modern earthquake activity and these faults. Since all of these Massachusettsevents were quite small, there were insufficient first motion data to compute focal mechanisms. The largest event detected during the year was a $m_{Lg}(f)=3.4$ shock centered 80 km NE of Ottawa, Ontario in Canada.

Publications


Abstracts


Figure 1. Seismicity recorded and located by the New England Seismic Network of Weston Observatory of Boston College from October 1, 1992 to September 30, 1993.
Investigations

This project was comprised of three separate studies. The common thread linking these studies together is that they all involve deployment and operation of seismic network instrumentation and analysis of seismic network data.

1) Development of seismic network data integration tools - Element II.2. The objective of this study was to develop and distribute hardware and software systems that facilitate seismic network data acquisition and analysis. We focused on the development of systems that allow for the integration of data from a wide range of field instrumentation, data formats, and computer technologies.

2) Investigation of Slumgullion landslide faults as analogs to crustal-scale faults - Element II.3. This was a pilot study to investigate the possibility that faulting observed in landslides might be analogous to crustal-scale faulting. The initial motivation for the study was the observation that the morphology associated with faulting is very similar in both landslides and on a crustal-scale. If it could be demonstrated that landslide faults behaved like crustal faults in other aspects, then studies of them might prove useful in advancing our understanding of crustal faulting and earthquake mechanics. The advantages of studying landslide faults relative to crustal faults is that the rate of deformation is approximately 200 times faster and the spatial scales are an order of magnitude smaller. Thus, field observations could be made much more quickly and simply. Our pilot study focused on a major landslide-bounding strike-slip fault on the Slumgullion landslide located in southwest Colorado. It included the deployment of a buried high-resolution digital creepmeter, a seismic network consisting of a digitally-recording phased-microarray and four analog seismographs, and geodetic surveying using GPS and optical technologies. We collaborated with scientists from the University of Colorado, Boulder.

3) Studies of the Little Skull Mountain, Nevada earthquake sequence - Element 1.1.1,II.2,II.4. This study examined various aspects of the Ms=5.4 June 29, 1992 Little Skull Mountain (LSM), Nevada earthquake.
   a. We collected and examined the evidence for remote triggering of the LSM earthquake by the Landers, CA earthquake. This evidence included seismic network catalog information and seismic data from the USNSN. Hypotheses about various mechanisms that might cause remote triggering were tested through theoretical modeling studies.
   b. A portable seismograph network was deployed immediately following the LSM earthquake. Because of the abundance of local sources, low noise environment, and relatively simple basin structures in the area, a phased-microarray was deployed as part of the network for the purpose of investigating site response characteristics.
   c. Data from many thousands of earthquakes preceding and following the LSM earthquake were analyzed so that hypocenters, focal mechanisms, and magnitudes could be estimated. These estimates were used to characterize the pattern of faulting and strain release that occurred during the LSM earthquake sequence. Data were obtained from the Southern Great Basin Seismic Network and a number of other adjacent regional networks, and from a network of portable seismographs deployed in the epicentral region.

Results

1) Development of seismic network data collection/integration tools - Element II.2.
   a. Programs for real-time acquisition and analysis of data from the newly installed U.S. National Seismograph Network (USNSN) station TPNV were developed and used.
b. Computer programs developed for use of USNSN telemetry were distributed to regional seismic network operators.
c. A PC-based hardware system for field acquisition and analysis of data from a variety of portable digital seismographs was designed and procured. Computer software for retrieving and analyzing data from portable digital seismographs was also developed for use in the field and office.

2) Investigation of Slumgullion landslide faults as analogs to crustal-scale faults - Element II.3. We demonstrated that landslide faulting shares many similarities with crustal-scale faulting and that it is feasible to collect a useful dataset using conventional instrumentation in a relatively short time (approximately one week). Analyses of data collected indicate the following characteristics of landslide faults.
a. Landslide faults creep at a steady rate modified by seasonal changes, similar to those observed on the San Andreas fault.
b. Landslide faults can store elastic strain energy as evidenced by creep events induced by several nearby small chemical explosions.
c. A variety of seismic signals were recorded. Some of these are clustered temporally and spatially and most probably are generated by landslide faulting.
d. Accurate GPS displacement vectors and rates were consistent with other observations. This suggested that use of GPS in landslide studies might eliminate the need for time-consuming, spatially-limited, conventional surveying.
e. Geodetic observations indicate block-like motion in the vicinity of the major slide-bounding fault.

a. We concluded that the LSM earthquake was triggered by the Landers, CA earthquake. Analyses showed the channeling of strain energy within a continuous band, manifest as seismic and aseismic signals, extending from the Landers to the LSM epicenters. We concluded that both static and dynamic strain changes associated with the Landers earthquake alone are too small to trigger failure. This suggests that the faults that produced triggered earthquakes must be pre-strained to near-failure levels and/or that other processes must be significant in causing remote triggering.
b. Analysis of phased-microarray data indicate that seismic ray paths can be quite irregular, even in relatively simple structures. This appears to result in considerable focusing of energy and thus amplification of ground motion.
c. The LSM earthquake appears to be a steeply-dipping normal-faulting event, typical of other moderate Basin and Range earthquakes. The surface trace of the probable rupture plane is within a sediment-filled basin and may corroborate other geophysical evidence for a buried fault beneath the basin. The post-seismic pattern of strain release was complex, showing a mixture of normal and strike-slip faulting on more than one rupture plane.

Reports
1) Development of seismic network data collection/integration tools - Element II.2.
No official reports or publications resulted from this work.

2) Investigation of Slumgullion landslide faults as analogs to crustal-scale faults - Element II.3.
Published

I, II

Published or in Press


In review


Other

Investigations

Maintenance and recording of 361 seismograph stations (504 components) located in Northern California, Central California and Oregon. Also recording 71 components from other agencies. The area covered is from Southern Oregon, south to Santa Maria.

Results

1. Site maintenance visits 565

2. Bench Maintenance Repair
   A. seismic VCO units 290
   B. summing amplifiers 33
   C. seismic test units 07
   D. VO2H/VO2L VCO units 53
   E. dc-dc converters 18

3. Production/Fabrication
   A. J512A VCO units 116
   B. J512B VCO units 04
   C. summing amplifier units 26
   D. lithium battery packs 121
   F. seismometer housing/cable 46

4. Rehabilitation: VCO enclosures 46

5. Computer site map plots
   A. new 23
   B. update 52

6. Discriminator repair and tuning (J120) 725 ea.

7. Revised and updated documentation on all wiring from telco input to discriminator output. (cusp, RTP, Motorola, PC, helicorder, etc).

8. Ordered parts for 220 ea J120 discriminators

9. Equipment Shipped:
   A. Cal Tech, Pasadena
      a. 54 ea. J512A vco’s
      b. 06 ea. J512B vco’s
      c. 100 ea. J120 discriminators
B. Mammouth, Seismic PC system
   a. 18 ea. J120 discriminators
   b. 01 ea. Wired discriminator rack
   c. 01 ea. power supply
   d. 01 ea. J. Ellis TCG

C. Pacific Tsunami Warming System (NOAA)
   a. 01 ea. J120 discriminator

D. CVO
   a. 16 ea. J120 discriminators

E. Lawrence Livermore National Laboratory
   a. 16 ea. J120 discriminators
   b. 01 ea. discriminator rack
   c. 16 ea. tuned V02H vco's

F. Hartnell College
   a. 02 ea. J120 discriminators

G. San Juan Bautista Visitor Center
   a. 02 ea. J120 discriminator

H. Chabot Observatory
   a. 01 ea. J120 discriminator

10. New installations
    A. CNIE, CNIV (Niles Canyon)
    B. MDRE, MDRN (Doe Ridge)
    C. MEME, MEMN (East Mammoth)
    D. MRHE, MRHN, MRHV, MRHZ (Rocky Hill)
    E. LAC (Anderson Creek)
    F. KEBV, KEBZ (Edson Butte, OR)
    G. VSP (Spence Mountain, OR)
    H. VRC (Rainbow Creek, OR)
    I. MDPR (Devil's Postpile Dilatometer)

11. Stations discontinued.
    A. HQRE, HQRN, HQRV, HQRZ (Quien Sabe Road)
    B. CPL (Palomares Road)

12. Supplied support for Refraction Experiments.

13. Provide technical support and maintenance on 7 visual recorders located in Northern Calif.
3D Dynamic Modeling of Earthquakes and Segmented Faults
9960-10446

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Program Element I

Investigations Undertaken:

During FY93 I investigated both static and dynamic stresses generated by earthquakes and their role in determining the locations and sizes of future events. My studies of dynamic stresses involved using three-dimensional numerical simulations to determine how fault geometry can control the rupture length and therefore the size (magnitude) of strike-slip earthquakes. The goal of this work is to determine what allows some strike-slip earthquakes to remain small or moderate-sized events, whereas other earthquakes cascade into much larger and more devastating events. This study has direct applications to numerous scenarios, including the recent M7.4 Landers, California earthquake. The Landers earthquake jumped across previously defined fault segment boundaries and cascaded from a predicted M6.5 earthquake into a much larger M7.4 earthquake with a 70 km rupture length and up to 6 meters of strike-slip offset.

My studies of static stress changes are in collaboration with Robert Simpson and involve analyzing how static stress changes generated by moderate to large earthquakes can affect nearby faults. This work has included analyzing the static stress changes generated by the 1992 M7.4 Landers, California earthquake. We have also begun an analysis of the static stress changes generated by the 1857 M8 Ft. Tejon, California earthquake, the largest known historical earthquake in California.

Results:

My results for the dynamic modeling during FY93 include a three-dimensional model for the next large earthquake on the San Jacinto fault. This model was initially applied to the San Jacinto Valley region to determine if the next ‘Anza Gap’ earthquake might cascade into a larger event by rupturing towards San Bernardino. Initial geological and seismicity studies of the faults near San Jacinto Valley had indicated that the two faults bounding the valley were vertical and separated by a 4-km wide stepover. If this were the case, then my numerical models, combined with the historical earthquake record indicate that the next Anza Gap earthquake should not jump between the two faults and should be the expected magnitude. More recent studies (Magistrale and Sanders, EOS Trans. AGU, Vol. 74, 1993) though are showing that the valley may actually be underlain by a single fault, and that the two faults at the earth’s surface actually merge at depth. If this is the case, then it appears that the stepover may not stop the next Anza Gap earthquake from cascading into a larger than expected earthquake. Numerical simulations of this late-breaking information will continue into FY94, as will applications to the San Jacinto fault further north, where Magistrale and Sanders find a 3-km wide right step.
Results (continued):

Research in FY93 also includes the start of a dynamic fault model for the 1992 Landers earthquake. This earthquake is the first case of an earthquake jumping between fault segments where sufficient data was collected to analyze the rupture process in detail. I am concluding that my numerical modeling results are consistent with what occurred during the Landers earthquake, and that the numerical results do indeed have potential applications for earthquake-size prediction. This result will be published in FY94.

My results for the static modeling during FY93 (in collaboration with Robert Simpson) include models for the effects of the M7.4 Landers earthquake on nearby southern California faults. We concluded that the Landers earthquake advanced the next large earthquake on the San Bernardino and Coachella Valley segments of the San Andreas fault and delayed earthquakes (although by not as long) on the Mojave segment. This earthquake also produced considerable static stress changes on the northern segments of the San Jacinto fault, and on faults to the north of Landers. Our results for the great 1857 earthquake indicate that the static stress changes generated by this earthquake may have "shut off" large earthquakes on faults which were relaxed for up to 50 years after the great event.

Reports Published (12):


Harris

Reports Published (continued):


EARTHQUAKE SOURCE AND EFFECT STUDIES

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Main Program Elements I.2, II.2, III.2

Investigations

1) Finite-fault, waveform inversion techniques are used to calculate the rupture histories of five eastern North American earthquakes (ENA): January 9, 1982 New Brunswick; October 5 and December 23, 1985 Nahanni; November 25, 1988 Saguenay; and December 25, 1989 Ungava earthquakes.

2) A hybrid, global search algorithm is developed for solution of nonlinear, multiparameter inverse problems and applied to the determination of earthquake source parameters, in particular the 1992 Landers, California, earthquake.

3) Ground motion records for a dense array of instruments on Robinwood Ridge, California, are studied to determine site and topographic effects for aftershocks of the 1989 Loma Prieta earthquake.

4) Modeling of a two-dimensional fault composed of patches with uniform statistical properties by Monte Carlo simulation and fitting of this model to smoothed peak acceleration data.

5) Spatial and temporal distributions of the central Peru subduction zone seismicity (1966 - 1991) including the aftershocks of the 1974 M_{w}8.1 Peru earthquake are examined.

6) Rupture history and fault complexity of the 23 November 1977 western Argentina earthquake are examined.

7) Little Skull Mountain, Nevada, earthquake. Focal mechanism solutions for the mainshock and 84 aftershocks were analysed using a stress-field inversion program to determine the best-fitting reduced stress tensors that describe the focal mechanism data.

8) New Madrid Seismic Zone earthquake simulation. The main objective of this study is to predict strong ground-motion parameters, such as PHA and PHV, that could be associated with a M 6.5 earthquake in the NMSZ, using plausible source scaling parameters, path and site attenuation and amplification factors, and stochastic slip with specified wavenumber transform when modeling various rupture scenarios on a 2-dimensional fault.
Results

1) Digital, world-wide records of P and SH waves are used to invert for rupture histories of the recent, larger, eastern North American (ENA) earthquakes. The data include a broad bandwidth to facilitate recovery of both source details and total moment. The inversion formulation allows estimates to be made of rise time and slip velocity, in addition to the spatial distribution of slip. Static stress drops averaged over the entire rupture surface range from a few tens of bars to just over 100 bars and are similar to values estimated for western United States earthquakes. Estimates of stress drop for spatially limited asperities are in the range of a few hundred bars, with the value for the Saguenay earthquake asperity being the largest. The variatoin in stress drop is considerable, but no evidence is seen for a scaling relation in which stress drop increases with moment. Maximum slip velocities also have a wide range, with the Saguenay and October 5 Nahanni earthquakes producing significantly larger values. Of the events studied, the Saguenay earthquake is unique in terms of its greater depth, spatially concentrated source, and large asperity stress drop.

2) Many interesting inverse problems in geophysics are nonlinear and multimodal (having many local minima). By combining simulated annealing with the downhill simplex method, a hybrid global search algorithm is obtained for these highly nonlinear problems. The hybrid algorithm shares the advantages of both local search methods that perform well if the local model is suitable and global methods that are able to explore the full model space efficiently. The hybrid algorithm also utilizes a larger and more complex memory to store information about the objective function than conventional simulated annealing. The new method has been shown to outperform simulated annealing and genetic algorithms for 1D acoustic waveform inversion problems.

The hybrid global search method is used to determine earthquake source parameters by the inversion of teleseismic waveform data. Desirable time-domain constraints, inversion for double-couple parameters rather than moment tensor elements, and inclusion of multiple sources lead to a nonlinear problem. Traditional approaches to this problem using iterative least squares are dependent on the starting model and the order in which sources are processed, and converge to local minima. The hybrid global method converges to the global minimum of a prescribed objective function. A three point-source parameterization of the 1992 Landers earthquake is used as an example. Parameters from the inversion are consistent with field observations and the moment release function is consistent with the observed spatial distribution of slip.

3) Following the 1989 Loma Prieta earthquake a dense array of 7 digitally-recorded, 3-component seismograph stations was deployed on Robinwood Ridge 7.3 km northwest of the epicenter. The purpose of this array was to investigate the cause of high levels of structural damage and ground cracking observed on the ridge crest. Aftershocks recorded by the array allow a comparison of ground motion up the slope of the ridge from the base to the crest. Interference between incident and diffracted waves causes a complex pattern of ground motion. An amplification factor of from 1.5 to 4.5 is seen for frequencies with wavelengths comparable to the base of the ridge, part of which may be caused by local site effects and part by topographic amplification. In addition, amplifications of up to a factor of 5 are seen at higher frequencies and are attributed to local site effects.
4) We investigated a 2-D source model to confirm behavior previously observed in smoothed representations of peak acceleration data. Our purpose was to improve our understanding of the basic properties of the peak acceleration data with a view to developing more reliable functional forms with which to represent peak acceleration attenuation. A fault rupture model composed of uniform-sized patches with uniform statistical properties was used to perform Monte Carlo simulation of peak acceleration for a range of magnitudes and distances. The model parameters are the mean and standard deviation of peak acceleration very near the patch, the patch size, a lower-limit cutoff for station accelerations (intended to simulate sampling bias due to triggering threshold), a peak acceleration upper-limit threshold for patches (intended to simulate the effect on peak acceleration of a rock strength limit), anelastic attenuation, and approximate peak-acceleration site effects. This earthquake source model, in contrast with earlier point-source stochastic models, produces peak-accelerations that saturate with magnitude at some distances and display distance-dependent saturation, as has been observed in the data. The model also reproduces distance-dependent reduction in scaling, that we previously hypothesized as due to sampling bias produced by an instrument-triggering threshold. Parameter variation studies and tuning of the model to fit observed data behavior allowed us to narrow the range of likely values of the parameters, although this is not the main point of the study. The patch distribution mean, for example, is most likely in the range 0.6-1.0 g, the distribution standard deviation is in the range 0.3-0.4 log units, patch size need be no greater than 3 km, and path anelastic attenuation, \( k \), appears to be magnitude dependent, ranging from 0.012 at magnitude 4 to 0.001 at magnitude 8. The complexity of peak acceleration behavior demonstrated by the data and confirmed by our model suggests that more complex regression models than have often been used in the past are required to fit the data. At the very least, distance-dependent magnitude scaling is required and a reasonable case can be made for magnitude-dependent anelastic attenuation. Furthermore, the data are biased by sampling restrictions, and, hence, fitting the data with models inadequate to represent these behaviors will produce predictions that are also biased. The prediction of peak acceleration is probably best accomplished by empirical, smoothed representations of the data in graphs or tables that have the sampling bias minimized, as in our earlier study or by model results that could be produced by this model. For example, to produce unbiased predictions one would fit the model to the data with a lower-limit threshold to establish to model parameters, but remove the lower-limit threshold when computing unbiased predictions.

5) The eight years of regional earthquakes that preceded the 1974 Peru earthquake were entirely downdip of the shallow-dipping subduction interface of the main shock. The largest earthquake of this preseismicity (\( M_S 6.1, h = 80 \text{ km}, \text{ Jan 5, 1974} \)) was a normal-faulting event located directly east of the main shock. Of the preseismicity, 5 events were located at the downdip edges of the eventual ruptures of the Oct. 3 (\( M_W 8.1 \)) and Nov. 9 (\( M_W 7.1 \)) earthquakes.

The aftershocks, relocated (JHD) using data from a temporary regional seismograph netwroek, remain among the best observed of any circum-Pacific subduction earthquake. Many of these aftershocks were concentrated near the downdip edge of the main shock rupture and further downdip beneath the Peruvian coast. Rupture maps for the main
shock (Hartzell and Langer, 1994) suggest that there must have been significant motion of the Nazca plate into the zone of plate bending at the Peru-Chile trench. Nevertheless, no aftershocks were observed near the trench and it is concluded that the rapid bending there must be aseismic. The many aftershocks downdip of the plate hinge (where the plate steepens by about 20°) suggest that there was motion along that steeper plate section. However, no aftershocks seem to be associated with the hinge area indicating that plate motion through the hinge also occurred aseismically.

6) Inversion of teleseismic, WWSSN, P- and SH waveforms provides estimates of slip distribution for the 23 November 1977 western Argentina earthquake. The inversion method uses a parameterization of the fault model allowing for multiple, sequential, rupture intervals that discretize the source rise-time and rupture time. Because there was no observed surface rupture, we used well-located aftershocks (determined by data from a local network) and mapped surficial geology to help constrain the model geometry. Several models have been tested with the most favorable being in two segments, the north segment is 40 km long and strikes at 345° while the south segment is 90 km long and strikes at 10°. Both segments dip to the east at 45°.

7) Well-constrained focal mechanism solutions were obtained for the Little Skull Mtn mainshock and 84 of the largest aftershocks from June 29 to Sept 24, 1992, yielding predominantly normal slip solutions for about 70% of these earthquakes, including the mainshock. Inputting these solutions into a stress-field inversion program written by John Gephart gives a range of plausible reduced stress tensors each of which could be associated with these mechanisms. This range includes strike-slip tensors and normal slip tensors, with slightly better but not statistically significant improvement associated with a normal-slip stress tensor (near vertical $\sigma_1$). Several of the focal mechanisms have shallow-dipping ($< 30°$) nodal planes, which are selected by the inversion as the best-fitting nodal planes to all of the best-fitting reduced stress tensors, suggesting the possibility of seismic failure on relatively shallow-dipping faults during the aftershock sequence. It is suggested that fluid pore pressures were increased in portions of the response zone for a period of time, on the order of a few weeks, inducing slip on fault segments that would be considered misoriented when using a standard Coulomb failure criterion and assuming $\approx$ hydrostatic pore pressures. (Also, earlier geologic investigations suggested that LSM is in a left-lateral strike-slip fault domain. The LSM mainshock and aftershocks, while not sufficient evidence to refute this model, are more consistent with a normal-slip fault domain, and more recent geologic investigations are apparently concluding that the strike-slip fault domain hypothesis is based on 12-10 million year old movement, and is not supported by more recent indicators, which are normal-slip. Such characterizations are important because LSM is about 20 km from the nation's only potential high-level, long-term civilian radwaste repository, at Yucca Mtn, Nev.)

8) A magnitude 6.5 earthquake at Risco, Missouri has been modeled. The fault plane extends the preferred nodal plane of the May 4, 1991, Risco, Missouri earthquake to an area that is appropriate to the larger-magnitude event. The slip distribution on the hypothetical fault is obtained by wavenumber filtering of random Gaussian noise, in an application of W. Joyner's simulate computer program. The source time function is of the Kostrov type,
with a corner-frequency proportional to the fault width. Unilateral rupture is specified in order to maximize the azimuthal effect of source directivity. Records of acceleration associated with this source and various $Q_s$ models at various real sites, including Reelfoot Dam, and hypothetical sites distributed around the fault, indicate that relatively high-$Q$ and a high stress parameter, $\Delta \sigma$, often associated with central US earthquakes, are quite capable of producing one to two $g$ PHAs (and higher) at sites 30 km from the fault at forward azimuths on Mississippi embayment soils. The computer program was tested using PHA data from many sites that recorded the bf M 6.5 Imperial Valley California earthquake of Oct 15, 1979. It was also tested using available NCEER data for the Risco, Mo., earthquake ($M_{Lg} = 4.6$) of May 4, 1991, with satisfactory results.

Reports


Investigations

The large number of recent events associated with the Big Bear-Landers earthquake sequence is providing a unique set of broadband data. This data set can be used in deriving detailed source characteristics and earth structure. In addition many of the historic events occurring along this extended zone have been recorded locally by relatively low gain long period and short period torsion instruments operated by Caltech (1930 to 1960) and by standard strong motion instruments. Some of the larger events $M>5$ can be seen on the old broadband instruments at Berkeley (Galitzins) regionally while still larger events $M>6$ can be observed teleseismically, (De Bilt, etc.).

To understand these seismograms and separate propagational distortions from source properties is relatively easy at teleseismic distances, but becomes more difficult at regional and local distances. Fortunately, the digital systems used in the TERRAscope array provide observations that greatly aid in establishing the nature of regional wave propagation. For example, the wide dynamic range allows motions from small events (aftershocks) to be compared with large events at the same site even though the motions can differ by several orders of magnitude. Signals at these distances have not suffered mantle attenuation and thus the broadband features of this system allow us to see obvious propagational effects (headwaves and critical reflections) and detailed source characteristics (near-field and source complexity).

The clearest lesson to date comes from events viewed through a short-period Wood-Anderson instrument (wa.sp) for similar paths where they are generally similar over several magnitude units. Apparently, the largest asperity dominates the wa.sp response for the larger events. This suggests that normal scaling laws such as $w^2$, $w^3$, etc. are not very dependable in characterizing earthquakes. Secondly, the propagational path is mostly responsible for the seismic signature at local and regional distances. Thus, knowledge of local seismicity and an extensive catalog of waveform data from known events for comparative analysis becomes particularly important.

Results

Several papers involving the waveform modeling of recent earthquakes have been published or are in press:

To date, we have determined a source rupture model for the 1992 Landers earthquake (Mw = 72) compatible with multiple data sets, spanning a frequency range from zero to 0.5 Hz. Geodetic survey displacements, near-field and regional strong motions, broadband teleseismic waveforms and surface offset measurements have all been used explicitly to constrain both the spatial and temporal slip variations along the model fault surface. Out fault parameterization involves a variable-slip, multiple-segment, finite-fault model which treats the diverse data sets in a self-consistent manner, allowing them to be inverted both independently and in unison. The high-quality data available for the Landers earthquake provide an unprecedented opportunity for direct comparison of rupture models determined from independent data sets that sample both a wide frequency range and a diverse spatial station orientation with respect to the earthquake slip and radiation pattern. In all models, consistent features include: 1) similar overall dislocation patterns and amplitudes with seismic moments of 7.7-8 x 10^27 dyne-cm (seismic potency of 2.3-2.7 km^3), 2) very heterogeneous, unilateral strike-slip distributed over a fault length of 65 km and over a width of at least 15 km, though slip is limited to shallower regions in some areas, 3) a total rupture duration of 24 sec and an average rupture velocity of 2.7 km/sec, and 4) substantial variations of slip with depth relative to measured surface offsets. The extended rupture length and duration of the Landers earthquake also allowed imaging of the propagating rupture front with better resolution than for those of prior shorter-duration, strike-slip events. Our imaging allows visualization of the rupture evolution, including local differences in slip durations and variations in rupture velocity. Rupture velocity decreases markedly at shallow depths as well as near regions of slip transfer from one fault segment to the next as rupture propagates northwestward along the multiply-segmented fault length. The rupture front slows as it reaches the northern limit of the Johnson Valley/Landers faults where slip is transferred to the southern Homestead Valley fault; an abrupt acceleration is apparent following the transfer. This process is repeated, and is more pronounced, as slip is again passed from the northern Homestead Valley fault to the Emerson fault. Although the largest surface offsets were observed at the northern end of the rupture, our modeling indicates that substantial rupture was also relatively shallow (less than 10 km) in this region.


Displacement seismograms recorded by TERRAscope for the June 28, 1992 Landers earthquake (Mw 8.3) are deterministically modeled using a forward, point-source summation technique. Although the data set is sparse, it was possible to robustly determine important rupture parameters such as gross slip distribution, rupture velocity, rise time and total source duration. The relatively simple approach lends itself to rapid application following large earthquakes, provided that a catalog of Green's functions appropriate for the region is available.

The fault used in the modeling of the Landers mainshock has a length of 70 km along strike and a width of 15 km along dip. A model was found in which the distribution and amplitude of slip at the surface matches the observed surface slip and provides a very good level of fit to the seismic data. Seismically, the Landers earthquake is characterized as two subevents. The peak slip of the first sub-event is 10 km north of the epicenter and the second is 40 km northwest along strike from the epicenter. The seismic moment is distributed as 2x10^26 dyne-cm to the first and 6x10^26 to the second subevents, respectively. It was assumed in our modeling that the distribution of seismic moment along strike was the same at all depths. This assumption implies that slip at depth is 69% of that at the surface due to differences in the material properties in the velocity model. The sensitivities of the source model to rupture velocity and dislocation rise time were examined. A rupture velocity of 2.9 km/s (80% of the shear wave velocity) and a rise time of 1 to 3 seconds were found to satisfy the data. The rise time is only a fraction of the total source process time of 24 seconds, and implies that slip on the fault occurred within a narrow band (3 to 10 km), at any instant during the rupture.
The June 28, 1992 Big Bear earthquake in southern California was assumed to have ruptured along a northeast-trending plane, as suggested by long-term aftershock distribution. No surface rupture was found, however, and mainshock locations determined from both strong motion and TERRAscope data are mutually consistent and do not lie on the assumed fault plane. An integrated study involving waveform modeling, directivity and seismicity analyses suggests a complex rupture pattern, with significant short- and long-period energy propagating northwest along the presumed conjugate fault-plane.


The October 4, 1987 aftershock (ML = 5.3) of the Whittier Narrows sequence and the June 28, 1991 Sierra Madre mainshock (ML = 5.8) are on a similar azimuth to stations overlying the deepest part of the Los Angeles sedimentary basin. The proximity of the Whittier Narrows sequence to the basin provides an opportunity to isolate the effects of the basin on wave propagation. A distinctive feature of records from basin stations recording the October 4th aftershock is the large amplitude of the first multiple (SS) on the tangential component. The amplitudes of the multiples are up to twice the direct SH phase on the tangential component. The distance from the aftershock to the stations in the basin is less than 25 km, and at such short range a horizontal seismic velocity gradient is needed to turn rays rapidly enough for large amplitude multiples to form. This is taken as a primary constraint in the construction of our two dimensional velocity model. A forward modeling approach is employed, using finite difference numerical techniques that produce double couple point source solutions. A model mimicking a recently constructed geologic cross section across the east edge of the L.A. Basin generates more phases than are seen in the seismic records. Simpler models based on dipping layers with low shear velocities in the top few layers fit the data better and the phases are more stable between receivers. The seismic velocity, depth, and dip of the layers are varied to fit the timing between the direct P, the direct S, and the first SH multiple. Including a steeply dipping west edge in the basin model has little effect on the synthetic waveforms except at distances near that basin edge. The timing and amplitude of the direct and first multiple SH pluses is well modeled, though the phase of the first multiple does not match the data. The Sierra Madre mainshock occurred about 25 km to the NE of the Whittier Narrows sequence. The model for Whittier Narrows was extended this distance, with a shallow basin between Whittier and the Sierra Madre hypocenter to account for the San Gabriel basin. Phases generated by the edge of the deep basin continue to dominate the synthetics, but this model generates a lengthy coda. This study indicates that specific phases produced by propagation effects through sedimentary basins, and with frequencies up to 1 Hz, can be explained by two dimensional seismic velocity models.
Regional Microearthquake Network in the Central Mississippi Valley

14-08-0001-A0619
Program Element 1
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Investigations

The purpose of the network is to monitor seismic activity in the Central Mississippi Valley Seismic zone, in which the large 1811-1812 New Madrid earthquakes occurred. The following section gives a summary of network observations from October 1992 through September 1993.

Results

During this time, 97 earthquakes were located by the regional telemetered microearthquake network operated by Saint Louis University for the U.S. Geological Survey and the Nuclear Regulatory Commission. Figure 1 shows 92 earthquakes located within a 4° x 5° region centered on 36.5°N and 89.5°W. The magnitudes are indicated by the size of the open symbols. Figure 2 shows the locations and magnitudes of 68 earthquakes located within a 1.5° x 1.5° region centered at 36.25°N and 89.75°W.

From October 1, 1992 through September 30, 1993, 110 teleseisms were recorded by the PC clone running the VENIX operating system. Epicentral coordinates were determined by assuming a plane wave front propagating across the network and using travel-time curves to determine back azimuth and slowness, and by assuming a focal depth of 15 kilometers using spherical geometry. Arrival time information for teleseismic P and PKP phases has been published in the quarterly earthquake bulletin.

The significant event of the year was USNRC termination of support for the regional seismic network. As of June 1, 1993 all telephone telemetry to USNSRC stations in Illinois, Indiana, Missouri and Arkansas was ended. This marked the end of 15 years of monitoring earthquakes in the broad geographical region for the USNRC.

The significant earthquakes occurring during this time include the following:

- October 1, 1992 (0240 UTC). mbLg 2.5 (GS). MD 2.6 (TEIC). Felt at Blytheville.
- December 17, 1992 (0718 UTC). Oklahoma. mbLg 3.6 (GS), 3.5 (TUL). Felt (IV) at Lindsay and (III) at Bradley and Elmore City. Felt in southern McClain and northern Garvin Counties.
• December 27, 1992 (1012 UTC). Cape Girardeau, Missouri region. mbLg 3.2 (GS), 3.2 (TUL). Felt (IV) at Oak Ridge and Pocahontas; (III) at Altenburg, Brazeau, Frohna, Old Appleton, Perryville and Uniontown. Also felt in the Cape Girardeau area. Felt (IV) at Anna and Wolf Lake, Illinois. December 27, 1992 (1014 UTC). Cape Girardeau, Missouri region.

• January 21, 1993 (1946 UTC). New Madrid, Missouri region. MD 3.0 (TEIC), 3.0 (SLM). mbLg 3.0 (GS). Felt (III) at Ridgely and Newbern, Tennessee. Felt (III) at Braggadocio, Missouri. Also felt at Miston and Wynnburg, Tennessee.

• January 29, 1993 (1356 UTC). Illinois. mbLg 3.2 (GS). MD 3.2 (SLM). Felt (III) at Herrick and Saint Peter. Felt (II) at Hagarstown and Saint Elmo.

• February 6, 1993 (0209 UTC). New Madrid, Missouri region. MD 3.5 (SLM), 3.5 (TEIC). mbLg 3.4 (GS), 3.3 (TUL). Felt (IV) at Sikeston; (III) at Grayridge, Lilbourn, Matthews and Parma; (II) at Caruthersville and East Prairie. Also felt at New Madrid. Felt (IV) in the Bogota-Miston-Ridgely area.
24 February, 1993 (1241 UTC). New Madrid, Missouri region. MD 2.8 (SLM).

March 2, 1993 (0029 UTC). New Madrid, Missouri region. MD 3.0 (SLM). mbLg 3.1 (GS). Felt (IV) at East Prairie, Kewanee and Lilbourn; (III) at Matthews and New Madrid; (II) at Portageville.

March 16, 1993 (0738 UTC). Arkansas. MD 3.0 (SLM), 3.0 (TEIC). mbLg 3.3 (GS). Felt at Marked Tree.

March 29, 1993 (1537 UTC). New Madrid, Missouri region. MD 2.7 (SLM), 2.5 (TEIC). mbLg 2.4 (GS). Felt at Catron.

March 31, 1993 (2023 UTC). New Madrid, Missouri region. MD 3.1 (SLM), 3.3 (TEIC). mbLg 3.3 (GS). Felt (V) at East Prairie, (IV) at Bertrand and (III) at Anniston, Kewanee and Matthews. Also felt at Charleston and Sikeston.
- April 2, 1993 (0128 UTC). Cape Girardeau, Missouri region. MD 2.5 (SLM), 2.5 (TEIC). mbLg 2.5 (GS). Felt (IV) at Cunningham and Kevil, Kentucky. Felt (III) at Barlow and La Center, Kentucky.

- April 2, 1993 (0302 UTC). Cape Girardeau, Missouri region. MD 2.5 (SLM), 2.6 (TEIC). mbLg 2.5 (GS). Felt (IV) at Cunningham and (III) at Kevil, Kentucky.

- April 28, 1993 (2240 UTC). New Madrid Missouri region. MD 3.5 (SLM). mbLg 3.6 (GS). Felt (IV) at Bogota, Finley, Lenox, Newbern and Ridgeley, Tennessee. Also felt (IV) at Caruthersville, Missouri. Felt (III) at Somerville, Tigrett and Trimble, Tennessee and at Steele, Missouri. Felt at Dyersburg, Tennessee.

- August 27, 1993 (0008 UTC). Eastern Missouri. MD 3.3 (SLM). mbLg 3.3 (GS). Felt (V) at Leadwood; (IV) at Desloge, French Village and New Offenburg; (III) at Cadet, Crystal City, Flat River, Fredericktown, Herculaneum, Irondale, Middlebrook, Potosi and Valles Mines; (II) at Park Hills. Felt at Dittmer, Pevely and Salem. Also felt at Waterloo, Illinois.

- September 24, 1993 (1827 UTC). New Madrid, Missouri region. MD 2.8 (SLM). mbLg 3.0 (GS). Felt (IV) at Marston and Parma. Felt (III) at Libbourn.

Publications

To support the USGS produced movie about New Madrid, Hidden Fury, and to respond to requests concerning seismicity at New Madrid, a 31 page report, New Madrid Earthquake Catalog Display, was prepared. This report features a graphical display of historical and instrumental seismicity at New Madrid and also contains the regional seismic network and Nuttli historical data bases with documentation on their formats. Copies have been provided to the USGS Golden, Reston, and to state agencies in Arkansas, Missouri and Illinois.
Cooperative New Madrid Seismic Network

14-08-0001-G1922  14-08-0001-G1923
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Program Element 1

Introduction

The object of this effort is to upgrade the regional seismic networks in the central Mississippi Valley to provide the data sets necessary for future research in the earthquake process and in earthquake generated ground motion.

In order to accomplish this, the satellite telemetry capability of the US National Seismic Network will be used to communicate between central data collection points at Memphis and St. Louis and the intelligent regional seismic network nodes to be placed at five sites in the region.

Major tasks involve the design and implementation of the data centers, the regional nodes at satellite uplink points, and the seismic sensors in the field.

Status

Network Design

The purpose of the original regional network deployment was to define seismicity patterns and recurrence. The purpose of the upgraded network is to continue these studies, but more importantly to address the following scientific tasks:

- On-scale recording of ground motions for earthquakes with magnitude less than 6 (reasonable expectation for the life of the network).
- Rapid determination of source parameters including source depth, moment tensor and source time function,
- Determination of attenuation of seismic ground motion in the distance range of 0 - 200 km for use in regionally specific seismic hazard studies, and
- Delineation of three dimensional seismic crustal structure within the region, since this will provide the means for estimating expected ground motions for future large earthquakes.

These scientific goals require different types of data sets:

- Waveform modeling of larger regional events requires approximately 2 minutes of broadband data sampled at 20 Hz.
- Delineation of regional earth structure requires the use of regional waveforms and also teleseismic signals, P, S and surface waves. Long period surface wave modeling could use 60 minute windows with sampling of 1 Hz.
Study of high frequency ground motion requires event segments sampled at least at 40 Hz.

To meet these goals with respect to ground motion, source and structural studies, the deployment of the network must be significantly different from its present form. Analog telemetry stations will still be required to monitor the seismicity near New Madrid proper and to provide information for earthquake location. However, a broad geographical distribution of broadband stations is required, such that stations cannot be interconnected by radio telemetry by distance. Figure 1 shows a possible distribution of broadband stations throughout the region. This distribution is made to monitor earthquakes and ground motions throughout the entire region (Figure 2).

![Fig. 1. Proposed distribution of broadband stations.](image)

**RFP**

An RFP has been submitted to manufacturers for equipment bids. This RFP reflects the evolution of the seismic network design. The requirement is that the stations indicated in Figure 1, be modern broadband digital stations with dialup capability - e.g., open stations. These stations will be interrogated daily and also following an earthquake by computer based control systems at the two universities.

RFPs will be evaluated at the end of December so that acquisition may begin in January. The spring of 1994 will be spent in site preparation with installation during the summer of 1994.

**Software Support**
Fig. 2. Central Mississippi Valley Earthquakes 1974-1992

Eric Haug has written software for VSAT communication. The code is named vsatrd, vsatsav and prvsatpkt. This code has been distributed to the Seismo Lab at Caltech, the University of Utah, Lamont-Doherty Earth Observatory, the University of Washington, and to Multimax, Inc. Distribution of the software is only permitted through Saint Louis University in order to provide unifying control over this code. Modifications and the experience of users will be incorporated to improve the code. Initial testing has highlighted problems with some computers keeping up with the 2K byte packets that the VSAT prefers to dump. The usefulness of different serial port hardware is being evaluated.
Pressure Solution, Crack Healing and Crustal Stress

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Program Element I

Investigations Undertaken

1. Laboratory Studies of Solution-Transport Deformation

Solution-transport processes such as pressure solution, crack healing and neck growth can be quite important in determining the rheology of fault zones and the evolution of rock physical properties. Our goal in this study is to provide fundamental constraints on the mechanisms and kinetics of these processes in quartzose rocks. Accordingly, we are carrying out a series of experiments on single mineral-mineral contacts using a unique hydrothermal vessel equipped with a sapphire optical window. In these experiments a convex quartz lens and a flat quartz lens are pressed together in water at temperatures of 400-600° C and water pressures of up to 2 kb. We continually observe the contact region and employ reflected-light interferometry to monitor the rate at which the lenses approach one another (converge) with time. In this manner we can independently determine the rates of pressure solution and neck growth as a function of temperature, effective normal stress, contact geometry, grain-boundary misorientation and second-phase mineralogy.

2. Field Investigation of Causes for Permeability Enhancement Accompanying the 1989 Loma Prieta Earthquake, Santa Cruz Mountains, California

The Loma Prieta earthquake (10/17/89, M-7.0) caused significant changes in the hydrology of the San Lorenzo River basin. These changes, consisting of stream-flow increases that persisted for several months after the earthquake and long-lived post-seismic lowering of the water table, are most readily explained by ground-motion induced permeability increases in the near surface aquifers and aquitards (Rojstaczer and Wolf, 1992). Two questions arise when examining permeability enhancement as a mechanism for these hydrologic changes: 1) What is the ambient state of stress and how might it interact with coseismic stress changes (either dynamic or static) to enhance the permeability of these aquifers through fracturing, fault reactivation, or other processes? and 2) What are the time constants associated with these permeability changes? To help answer these questions, we have been collaborating with Stuart Rojstaczer of Duke University to measure stress magnitudes and orientations, fracture and matrix permeabilities, and the orientations of natural fractures and faults in a 170-m-deep well drilled at the top of a granodiorite ridge in the Santa Cruz Mountains near Ben Lomand, California. This project was begun in FY 1993 and is continuing into FY 1994.

3. Shallow In-Situ Stresses in Fractured Granitic Rock at Wawona, Yosemite National Park, California

This study, which involved hydrologists, geophysicists and geochemists from the USGS and the U.S. Department of Energy, was conducted to understand the nature, timing and extent of ground water flow in the fractured granitic aquifer beneath Yosemite National Park. Our role in
this study was to make hydraulic fracturing stress measurements in two shallow wells drilled by
the National Park Service near the town of Wawona to understand the nature and origin of the
shallow stress field in this area. In coordination with in-situ permeability and geochemical studies
by other investigations, our investigations will help determine if and in what manner these stresses
might control the orientations of permeable fractures and faults in this aquifer.

4. Planning and Coordination of Scientific Drilling in the San Andreas Fault zone and Associated
Site Characterization Studies

In collaboration with Mark Zoback (Stanford University), Lee Younker (Lawrence Livermore
National Laboratory) and William Ellsworth (USGS, Menlo Park), we have been leading an
international team of scientists and engineers in a long-term proposal to conduct detailed geological
and geophysical site-characterization studies along the San Andreas fault zone, culminating in the
drilling of inclined core holes through the San Andreas fault at one site at depths of up to 10 km.
Through an integrated program of site-characterization studies, down-hole measurements,
laboratory experiments on recovered materials and long-term fault zone monitoring, we will obtain
fundamental constraints on the structure, composition, mechanical behavior and physical state of
an active, major plate-boundary fault. This project would most likely occur in the context of an
International Continental Drilling Program currently being developed by a number of countries,
with financial, technical and scientific participation by as many international partners as possible.

5. Convening of USGS Red-Book Conference on the Mechanical Involvement of Fluids in
Faulting

A “Red-Book” Conference on the Mechanical Effects of Fluid in Faulting was sponsored by
the USGS under the auspices of the National Earthquake Hazards Reduction Program (NEHRP) at
Fish Camp, CA, between June 6 and June 10, 1993. The co-convenors were Steve Hickman
(USGS, Menlo Park), Rick Sibson (University of Otago, New Zealand) and Ron Bruhn
(University of Utah). The purpose of the conference was to discuss current ideas and plan future
research on the role of fluids in fault mechanics, earthquake generation and mineralization.
Perturbations to the hydrological regime related to faulting and earthquakes were also discussed.

Results

1. Laboratory Studies of Solution-Transport Deformation

In FY 1993, we completed the design and construction of all components to be used in the
single-contact experiments; assembled, tested and calibrated these components; established sample-
preparation procedures; and performed our first experiments. These initial experiments were
performed using two polished quartz lenses pressed together under a load of 5.2 Newtons in
distilled water at 150 MPa fluid pressure and a temperature of 520° C. In-situ monitoring of
contact geometry and interference fringes showed no discernible convergence (pressure solution)
between the two lenses but did show the development of a fine-scale dendritic morphology at the
contact spot similar to microstructures observed during crack healing experiments conducted in
quartz using closed hydrothermal bombs (e.g. Brantley et al, 1990). Interestingly, however, the
rate at which the contact spot (“neck”) grew with time in our experiments was about 10-20 times
dlower than expected based upon simple extrapolations of intragranular crack healing rates for
quartz determined by Brantley et al. (1990). We believe that the slow neck growth rates we
observed may be due, at least in part, to the retarding effects of grain boundary energy on neck-
growth. The latter effect has been theoretically predicted as a consequence of the balance of
interfacial tensions at the intersection between a grain boundary and two solid-liquid interfaces and
has been experimentally confirmed in the halite/brine system (Hickman and Evans, 1992). If these
early results from our single-contact quartz experiments are borne out by further experimentation,
our results could profoundly alter commonly-held views of the rates at which grain-boundary cracks or pores might heal (i.e. disappear) with time in the mid to lower crust.

2. Field Investigation of Causes for Permeability Enhancement Accompanying the 1989 Loma Prieta Earthquake, Santa Cruz Mountains, California

Borehole televiewer and television logging in the Ben Lomand well has revealed numerous fractures and faults with thicknesses of up to several cm. The great majority of these fractures strike N-NW and dip 40-70° to the east. To date, we have conducted four hydraulic fracturing stress measurements in this well at depths of 30-100 m, using a new wireline packer system incorporating real-time digital telemetry of down-hole test-interval pressure, packer pressure and flow rate. Analysis of these data show that the magnitude of the least horizontal principal stress (Shmin) is equal to or slightly less than the calculated vertical stress (Sv), indicating a stress regime transitional between reverse and strike-slip faulting. The four hydraulic fracture orientations obtained thus far indicate that the direction of the maximum horizontal principal stress (Shmax) is N10°W ± 20°, parallel to the ridge axis (suggesting topographic control of the stress field) and the strike of most of the natural fractures and faults in this well. Thus, most of these fractures and faults are favorably oriented for normal faulting. Analysis of the potential for frictional failure on these planes using simple frictional faulting theory and coefficients of friction of 0.5-3.0 (as appropriate for normal stresses < 5 MPa [Byerlee, 1978]) indicates that normal faulting failure could be induced at this site by a reduction in Shmin of about 0.5-1.0 MPa. Simple calculations of dynamic stress perturbations expected at this site during the 1989 Loma Prieta earthquake indicate that cyclic perturbations to Shmin on the order of 8-12 bars are indeed possible. In contrast, calculations of static stress perturbations due to the Loma Prieta earthquake (R. Simpson, written comm, 1993) indicate that long-term stress changes at this site resulting from the Loma Prieta earthquake would have little effect on the propensity for frictional failure on the faults/fractures observed in this well. Thus, we propose that these features represent shallow normal faults activated by earthquake-induced strong ground motion and that these faults, in turn, may be responsible for the coseismic permeability enhancement inferred during the Loma Prieta earthquake. As a further test of this hypothesis, in the coming year will be using our wireline packer system to measure the permeability of individual fractures and fault zones of differing orientations to determine the extent of permeability anisotropy and the manner in which this anisotropy, if it exists, is aligned with the in-situ stresses.

To examine the time scales associated with the inferred permeability increases, Stuart Rojstaczer has obtained water quality samples from over 100 springs and streams in the drainage basin over a period of two summers. Analysis of water chemistry data from the summer of 1992 suggested that increases in dissolved ions associated with the earthquake were still present in many areas. However, because of the effects of drought, interpretation of these results was at least partly ambiguous. He reoccupied over 30 of these sites during the summer of 1993, a year with significant precipitation. Dissolved ion concentrations in these regions were still elevated relative to historically high levels, indicating that the earthquake-induced permeability increases are long-lived.

3. Shallow In-Situ Stresses in Fractured Granitic Rock at Wawona, Yosemite National Park, California

A total of 12 stress measurements were made in two test wells at Wawona. In both wells, the magnitudes of Shmin and Shmax relative to Sv indicate a reverse-faulting stress regime at depths less than about 200 m that is transitional to strike-slip faulting at greater depths. The magnitudes of the horizontal principal stresses in the upper 100 m of these wells are extremely high, with Shmax attaining a maximum magnitude of about 13 MPa at a depth of 50 m. The corresponding differential stresses (Shmax - Sv) are roughly twice as great as predicted using laboratory coefficients of friction of 0.6 to 1.0 (as appropriate for normal stresses > 5 MPa [Byerlee, 1978]).
As Wawona is located in a topographically rugged area that has experienced rapid erosion, we attribute these high horizontal stresses to a combination of near-surface residual stresses and topographic effects (e.g. McGarr, 1988; Liu and Zoback, 1992). Based on borehole televiewer logs conducted in these wells, we hypothesize that these high differential stresses can be maintained because of the paucity of natural fractures or faults that are favorably oriented for reverse faulting at shallow depths. In fact, the observation that most of the fractures in the upper few hundred meters of these wells are sub-horizontal is consistent both with our stress measurements (i.e. vertical stress << both horizontal principal stresses) and the presence of pervasive exfoliation in this area.

Orientations of the hydraulic fractures created during our tests indicate that $S_{H\text{max}}$ at Wawona is directed N59°W±15°. This orientation departs significantly from the roughly north-south to northeast $S_{H\text{max}}$ directions observed on either side of the central Sierra Nevada Mountains (Zoback and Zoback, 1989), but is subparallel to the overall trend of the valley of the South Fork Merced River at Wawona, further suggesting topographic control of the local stress field. Using the three-dimensional topographic stress model of Liu and Zoback (1992) in conjunction with digital elevation data for this area indicates that the orientation of $S_{H\text{max}}$ at Wawona can be explained through gravitational stresses induced by the local topography. The measured magnitudes of the horizontal stresses, however, are higher than predicted by simple gravitational loading models, suggesting that residual and/or thermal stresses might contribute significantly to the shallow stress regime in the Sierra Nevada Mountains. Analysis of pumping tests conducted by the USGS Water Resources Division (Morin and Borchers, 1993) shows that the most permeable fractures in these wells tend to be perpendicular to the least principal stress at depths <200 m but are favorably oriented for strike-slip faulting at greater depths, indicating that the permeability tensor in these granites is strongly influenced by the in-situ stress field.

4. Planning and Coordination of Scientific Drilling in the San Andreas Fault zone and Associated Site Characterization Studies

In December of 1992 we convened a workshop on the San Andreas fault zone drilling project at Asilomar, California. The purpose of this workshop, which was attended by 113 scientists and engineers from seven different countries, was to facilitate a broad-based scientific discussion of the scientific issues that could be addressed by deep drilling in the San Andreas fault, to identify potential drilling sites and to outline the types of site characterization studies that would be required to select the best possible site for the deep San Andreas hole.

Starting with 18 potential drilling areas identified at Asilomar, we held two meetings at the USGS in Menlo Park, California, with the Site Selection Committee and resident experts. As a result of these meetings, four segments were selected for further study: 1) the Mojave segment of the San Andreas between Leona Valley and Big Pine; 2) the Carrizo Plain between Highways 58 and 33/166; 3) the San Francisco Peninsula between Los Altos and Daly City; and 4) the Northern Gabilan Range between the Cienega winery and Melendy Ranch. During the past eight months, we have been coordinating proposals by individual investigators for site characterization studies. In June and July of 1993, about 25 proposals were submitted to the U.S. Geological Survey, the National Science Foundation and the U.S. Department of Energy to conduct preliminary geological, seismological, potential field, hydrological and borehole geophysical investigations along these four segments.

Our goal during the site-characterization phase of this project is to build a suite of comparative models of the geology, crustal structure, geophysical environment, hydrology, seismotectonics and fault-movement history at each of the 4 candidate sites. These investigations will be conducted by individual investigators, each of whom will contribute their results to a common data base. Through this process, we will deepen and extend our knowledge of the fault as a whole, whether or not the proposed 10-km-deep hole is ever drilled. Collectively, these studies will have a major
impact on our understanding of the structure and physical properties of the San Andreas fault system. They will also form a critical framework for applying the knowledge gained in the deep San Andreas hole to other segments of the fault and other tectonic environments.

5. **Convening of USGS Red-Book Conference on the Mechanical Involvement of Fluids in Faulting**

This conference was highly successful and was attended by a diverse group of 45 scientists, including people working in electrical and magnetic methods, geochemistry, hydrology, ore deposits, rock mechanics, seismology and structural geology. Topics addressed included evidence for fluid involvement in faulting and the nature of deep crustal fluid reservoirs, the composition of fault-zone fluids and fluid transport properties, coupled mechanical and hydrological processes in faulting, and the chemical effects of fluids on fault rheology. Very lively discussions centered on the origin and nature of fluid pressure compartments and their role in triggering instability, the evaluation of evidence for or against abnormally high fluid pressures during faulting, and processes that perturb the hydrological regime following earthquakes. Rick Sibson led a one-day field trip through the mesothermal quartz-vein gold deposits of the Mother Lode District, where participants saw and discussed evidence for high fluid pressures in exhumed reverse fault zones.

Participants provided extended abstracts and presented poster displays at the meeting, with poster sessions being followed by moderated group discussions. The workshop proceedings will be published as a USGS Red-Book volume. Selected articles arising from this workshop will be published as a special issue of the *Journal of Geophysical Research*.

**References Cited:**


**Papers and Abstracts Published or In Press, FY 1993:**


The Cooperative New Madrid Seismic Network (CNMSN) is being jointly developed by the Center for Earthquake Research and Information (CERI) at Memphis State University (MSU) and Saint Louis University (SLU) to both replace and upgrade the previous Memphis Area Regional Seismic Network (MARSN) and the Central Mississippi Valley Seismic Network. The new network will be fully integrated into the National Seismic Network (NSN). In addition, a cooperative agreement with the Tennessee Valley Authority (TVA) will permit using the TVA microwave network for seismic data transmission. This will effectively merge the CNMSN, the TVA network, and the Southern Appalachian Cooperative Seismic Network (SACSN) into a single large regional network providing coverage over a much larger area than any of the previous networks. Activity during the past year has concentrated on specifying the specific scientific and public service goals of the upgrade, the testing and development of hardware and software to meet these goals, and the purchase and installation of equipment to implement the network.

The new network will be composed of two complementary components, a dense distribution of short period seismometers focusing on the most active region of the New Madrid Seismic Zone within a larger regional but sparse distribution of broad-band seismometers. The broad-band sensors will provide state-of-the-art digital seismic data for advanced scientific research of topics such as the wave propagation properties of the Mississippi Embayment and the deep structure of the Central U.S. These studies will be important for the estimation of ground shaking in cities such as Memphis and the results will be immediately useful in seismic zoning, development of building codes, etc. Digital broad-band data will be collected at CERI/MSU through several technologies including satellite telemetry through the USGS NSN, two way digital telemetry using new communication technologies through existing FM radios, and the TVA microwave network.
Several VSATs have been installed and tested and the parts of the digital telemetry hardware have been tested but still lack integration. The short-period network will provide high quality location and magnitudes for seismic activity in the New Madrid Seismic Zone area. These systems will use analog telemetry with some form of gain ranging to increase the total dynamic range. The data will be recorded digitally and be available in real-time, which is important to meet the goal of providing timely information about earthquakes to the public and to emergency response services.

One important accomplishment of the past year was the upgrading and re-opening of the old WWSSN site at Oxford, MS. This station had been closed for almost 20 years. The site was refurbished and a digitally recording broad-band instrument was installed. Data from this instrument are now being sent in real time directly to the USGS in Golden Colorado through a satellite link.

The last year has seen the finalizing of a network plan. The plan was improved significantly by several developments that occurred at the same time. These developments include but are not limited to:

- the regional integration of three networks (CNMSN, TVA and SACSN) that the TVA microwave network made possible. The TVA microwave network will also improve the quality of the data from many sites by allowing transmission of digital data.

- the development of less expensive broad-band instruments, specifically the Guralp CMG-40T, which permitted the development of the regional broad-band component within our budget constraints.

- the development of new modem technologies and “intelligent” digitizers permit for the first time cost effective reliable digital transmission from the broad-band stations.

- the development of PANDA II and similar gain ranged systems at CERI for inexpensive real-time transmission of short period data with sufficient total dynamic range to prevent clipping by moderate sized (4+-5) events in the New Madrid Seismic Zone.

Significant work still remains to be done, but the plan that we are now implementing can be substantially completed by the end of the final year of funding.

Publications:


Imaging of fault zone geometry in the central New Madrid seismic zone using PANDA data, presented in the annual Eastern Seismological Society Meeting, Richmond, October, 1992, Y.T. Yang, J.M. Chiu, and A.C. Johnston.

Crustal velocity studies in the New Madrid seismic zone from USGS explosions recorded by the PANDA seismic array, presented in the annual Eastern Seismological Society Meeting, Richmond, October, 1992, Z.S. Liaw, J.M. Chiu, and A.C. Johnston.

The Southern Appalachian Cooperative Seismic Network (SACSN) is being developed by the Center for Earthquake Research and Information (CERI) at Memphis State University (MSU) and the Seismological Observatory at Virginia Polytechnic Institute and State University (VPI) to both replace and upgrade the previous Southern Appalachians Regional Seismic Network (SARSN). The new network will be integrated into the National Seismic Network (NSN). The Tennessee Valley Authority (TVA) and the University of North Carolina at Chapel Hill (UNC) also participate in SACSN through a sub-contract with CERI. A recent expansion of the cooperation with TVA will permit use the TVA microwave network for seismic data transmission. This will effectively merge the SACSN, the TVA network, and the Cooperative New Madrid Seismic Network (CNMSN) into a single large regional network providing coverage over a much larger area than any of the previous networks. Activity during the past year has concentrated on specifying the specific scientific and public service goals of the upgrade, the testing and development of hardware and software to meet these goals, and the purchase and installation of equipment to implement the network.

The design of the new network had several important goals:

- ending our dependence on expensive dedicated telephone lines.

- upgrading the network from single component stations to three component stations.

- the integration of several pre-existing networks into a single large network that both covers a wider area and provides higher quality data.

- integration of the new network into the NSN through satellite telemetry.
At this time the telephone service has terminated, most of the radio shots have been reconfigured and a PC based digital data collection facility has been installed at the TVA office in Knoxville. The new network configuration uses analog telemetry to send the seismic data to nodes of the TVA or UNC microwave networks. Once on the microwave network the data are routed to TVA and UNC. A microwave link to CERI is to be installed in the near future and satellite telemetry or Internet will be used to connect UNC with TVA and CERI.

The next step is the upgrading of all stations to 3 components. This will be accomplished by using both S-13 1 Hz instruments and L-28 4.5 Hz geophones. Gain ranged PANDA II analog telemetry, developed at CERI, will be used to increase the total dynamic range of the network.

Finally the network will be integrated into the NSN through several satellite communication links (VSAT).

The last year has seen the finalizing of a network plan. The most significant element of the plan that occurred during the last year was the regional integration of three networks (CNMSN, TVA and SACSN) that the TVA microwave network made possible.

Significant work still remains to be done, but there are no new untried technologies in the plan and we should have the upgrade basically finished by the end of the final year of funding.
Title: Earthquake and Seismicity Research Using SCARLET and CEDAR
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Program Element: I.1

Investigations:
1. The Energy Release by Earthquakes in Southern California
2. Crustal Structure in the Rupture Zone of the 1992 Landers Earthquake
3. Excitation of Long-Period Waves from the 1992 Landers Earthquake

Results:
1. We used a method developed by Kanamori et al. (1993) to determine the amount of energy released by recent major earthquakes in southern California. The main objective is to interpret the data in terms of mechanics of earthquakes. Since the results will be published in Kanamori (1994), we briefly summarize the conclusion.

Kanamori et al (1993) estimated the energy $E_S$ released by earthquakes using the high-quality broadband data which has recently become available in southern California. We determined the dynamic stress drops from the ratio of $E_S$ and the seismic moment $M_0$ for the 1989 Montebello earthquake ($M=4.6$), the 1989 Pasadena earthquake ($M=4.9$), the 1991 Sierra Madre earthquake ($M=5.8$), the 1992 Joshua Tree earthquake ($M=6.1$), the 1992 Big Bear earthquake ($M=6.4$), and the 1992 Landers earthquake ($M=7.3$). The stress drops for these events are in a range of 50 to 300 bars which are significantly higher than those for many large earthquakes elsewhere computed by Kikuchi & Fukao (1988). This difference can be interpreted as due to the long repeat times of these earthquakes in southern California.

The implication is that the strength of a fault increases with the time during which the two sides of the fault have been locked. The repeat time of major earthquakes on the frontal fault system where the Pasadena and the Sierra Madre earthquakes occurred is believed to be very long, a few thousand years (e.g., Crook et al 1987). Also the repeat time of the faults in the eastern Mojave desert where the Joshua Tree, the Big Bear and the Landers earthquakes occurred is thought to be very long (e.g., Sieh et al 1993). Since no measurements of $E_S/M_0$ have been made yet for earthquakes on faults with short repeat times in southern California, we cannot directly compare the dynamic stress drop for earthquakes with long and short repeat times in southern California.

As many studies have demonstrated, the heterogeneity of mechanical properties along a fault inferred from complexity of rupture patterns is
probably one of the most important elements of earthquake faults. Different
segments may have drastically different strengths and frictional
characteristics so that it would be necessary to consider different rupture
mechanisms for different segments. When a rupture occurs over a long
fault, different segments interact with each other in a complex fashion,
thereby causing complex seismic radiation as observed.

Mechanical properties of faults may be controlled by many factors:
lithology in the fault zone, temperature, pore pressure, fault geometry, fault
orientation with respect to tectonic stress, and slip rates. Rupture
initiation, propagation and cessation are all controlled by the mechanical
properties of each segment. The overall rupture patterns in each seismic
cycle (characteristic versus non-characteristic) depend on how different
fault segments interact with each other.

2. We inverted about 145,000 P-wave travel times from 3740
aftershocks of the Landers earthquake recorded by the southern California
Seismic Network to determine the crustal structure in the Landers area.
Since the results were published in Zhao and Kanamori (1993). We briefly
summarize the conclusion.

A detailed P-wave image is determined with a spatial resolution of
about 5 km and hypocentral locations are improved with the obtained 3-D
velocity model. Large velocity variations amounting to 6% are found in the
aftershock region. Most of the aftershocks are found to occur in relatively
high velocity (high-V) areas. Clusters of the aftershocks are separated by
low velocity (low-V) zones. The high-V areas are considered to be strong
and brittle parts of the fault zone which generate earthquakes. In contrast,
low-V areas are more ductile and weaker, where aseismic deformation is
more likely to take place.

3. The 1992 Landers earthquake ($M_w=7.3$) occurred in the middle of
the TERRAscope network. Long-period Rayleigh waves recorded at the
TERRAscope stations ($\Delta<3^\circ$) after traveling around the Earth show large
amplitude anomalies, one order of magnitude larger than spherical Earth
predictions up to a period of about 600 s. The ground motions over the
epicentral region at and after the arrival of R4-5 are in phase at all stations.
These observations are inconsistent with the nearly vertical strike slip
mechanism of the Landers earthquake. Synthetic seismograms for a
rotating, elliptic and laterally heterogeneous Earth model calculated by the
variational method agree well with the observed waveforms. Calculations
for various 3D Earth models demonstrate that the amplitudes are very
sensitive to the large scale aspherical structure in the crust and the mantle.
The anomalies for modes shorter than 300 s period can be explained by
lateral heterogeneity shallower than the upper mantle. Rotation of the
Earth and lower mantle heterogeneity are required to explain mode
amplitudes at longer periods. Current whole mantle seismic tomographic
models can fully explain the observed amplitudes longer than 300 s. To
assess the effect of the high order lateral heterogeneity in the mantle more
precise estimates of the crustal correction are required.
Reports (reports in press are included):


Title: Systematic Monitoring of Slow Earthquakes in the Los Angeles Basin
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Program Element: I.1

Investigations:

Although the main objective of this project is to develop a method for systematic monitoring of slow earthquakes, the nature of slow earthquakes is not fully understood yet. To improve our understanding of the nature of slow earthquakes, we made a detailed investigation of a few slow earthquakes as a part of this project. The following investigations were made.

1. A slow tsunami earthquake
2. W phase
3. Development of a method for systematic detection of slow earthquakes

Results:

1. The 1992 Nicaragua earthquake was a 'tsunami earthquake'; that is, it generated tsunamis disproportionately large for its surface-wave magnitude, $M_S$. The moment magnitude, $M_w$, determined from long-period (250-s) surface waves, was 7.6, significantly larger than the 20-s $M_S$ of 7; this $M_S-M_w$ disparity is also characteristic of tsunami earthquakes. The Nicaragua earthquake is the first tsunami earthquake to be captured by modern broadband seismic networks. The Nicaragua earthquake was a slow thrust earthquake which occurred on the subduction interface between the Cocos and North American plate, and because of the absence of sediments on the trench floor offshore of Nicaragua, the slip propagated updip all the way to the ocean bottom, exciting large tsunamis. The occurrence of slip on a plate interface filled with soft subducted sediments caused the rupture process to be slower than in ordinary subduction-zone thrust earthquakes.

2. The recent Nicaragua tsunami earthquake (September 2, 1992) produced a distinct ramp-like long-period (up to 1000 sec) phase which begins between $P$ and $S$ waves on displacement seismograms. In terms of ray theory, this phase consists of long-period $P$, $PP$, $S$, $SS$, $SP$, $PS$, etc. and its propagation mechanism is similar to that of a whispering gallery. In terms of normal-mode theory, it represents a group of higher-mode Rayleigh waves with a group velocity close to, but slower than, that of $P$ wave. This phase has not
been recognized as a distinct phase in the seismological practice because of clipping of seismograms for very large earthquakes. With the advent of modern wide-dynamic range seismographs, this phase can be easily identified for all large earthquakes. This phase will be useful for identifying slow earthquakes, determining whether slow deformation is precursory or coseismic to the regular short-period energy release, and determining velocity structures between the source and the station; this phase is called the "W phase".

3. We analyzed 1 sample/sec continuous TERRAscope data to look for anomalous slow events. Our method consists of subdividing the continuous time series for each TERRAscope station into a series of overlapping time windows, each 30 min long, and spectral analyzing over a period range of 2 to 1000 sec range. The result is a time-frequency plot for each station. This plot also includes the known local and teleseismic events for reference. Since these slow events are most likely to be triggered by a regular seismic event, detection of slow events will be facilitated by inclusion of regular events.

Our preliminary results demonstrate that the time-frequency displays are very effective for quickly scanning large amounts of data to monitor anomalous seismic radiation which cannot be easily detected by the traditional method of seismogram reading.

To determine an appropriate amplitude scale we first analyzed data for quiet days which do not contain any large local or teleseismic events. The spectrum is taken from the vertical component of long-period channel of PAS.

We examined the records from PAS for two and half months (part of February, April, and May of 1992), and found about 10 anomalous events. These events are very similar to the known slow event near Pasadena which occurred in 1988 (Kanamori, 1989). To verify the observations at Pasadena, we examined the data from USC (University of Southern California); unfortunately, the USC site is too noisy to detect any of these. We have recently installed another site at Rancho Palos Verdes, and we will examine the data from this station for verification.

Publications:


Investigations

Continued soil-gas radon survey across several faults in California and China. Continued continuous radon monitoring at two water wells in San Juan Bautista, California. Discontinued other hydraulic and chemical measurements because of lack of funding and logistic supports.

Results

Radon Anomalies on Active Faults

A repeat survey of soil-gas radon concentration was conducted across the Calaveras fault at Seventh Street in Hollister, California on September 30 and October 1, 1993. The result (Figure 2) shows a similar feature as the earlier survey conducted there in July 1992 (Figure 1), namely, double peaks separated by about 100 m on both sides of the creeping zone delineated by the offset sidewalks and a USGS creepmeter. Soil-gas samples were collected by W.C. Evans and analyzed with a gas chromatograph; the result shows a similar carbon-dioxide profile as radon and an inverted oxygen profile (lower oxygen values at sites where radon and carbon-dioxide concentration were high). This result supports the previously proposed mechanism for the observed radon anomalies, namely, by an upward soil-gas flow in the high-permeability fractured rocks on both sides of the fault-gouge zone. However, the nitrogen contents of the gas samples do not show any significant variation along the survey line, perhaps because of fertilizer used at the site (on a lawn in a park).

Similar radon surveys were conducted across several active faults and ground fractures in mainland China and Taiwan in October and November 1993. Anomalously high radon emanations were found on all the surveyed faults and fractures.

Reports

King, C.-Y., 1992, Comments on "\(^{222}\text{Rn}\) premonitory signals for earthquake" by R.L. Fleischer, A. Mogro-Campero, Eos, American Geophysical Union Transactions, 73 (48), 517-518.


King, C.-Y., Zhang, W., and King, B.-S., 1993, Radon anomalies on three types of faults in California (abs.), *Abstracts Volume of 2nd International Colloquium on Gas Geochemistry*, Besançon, France.
Investigations Undertaken: We continue to explore the physics of earthquakes along active plate boundaries by a multidisciplinary approach involving seismology, numerical modelling and laboratory investigations. Our main objective is to better understand the tectonic and seismic implications of kinetically-controlled metamorphic processes that occur in subduction zones. Intraslab earthquakes at intermediate depths (40-300 km) pose a significant seismic hazard worldwide. Since 1959, there have been over 600 with moment magnitudes $M_w \geq 6.0$, nearly 100 with $M_w \geq 7.0$ and several with $M_w \geq 8.0$ (Astiz et al., 1988; Okal, 1992). Harvard CMT Catalogue (1983 to 1993). Near populated areas in Central America, Southern Mexico, the Japanese Archipelago, Taiwan, South America, and Roumania, these earthquakes (and similar ones that have occurred earlier in this century) have caused appreciable loss of life and property damage. Closer to home, such damaging earthquakes have occurred in the subducting Juan de Fuca slab beneath the Puget Sound region and there is potential for such events in the southern Alaska. Even though subduction has ceased beneath much of Northern California as the Mendicino Triple Junction migrated north in the late Cenozoic, it is unlikely that the fossil subducted Juan de Fuca/Farallon slab and the overlying North America plate forearc have completely reached thermal and thermodynamic equilibrium. Metamorphic reactions and in particular fluids liberated by dehydration in that setting may be influencing the physics of the San Andreas fault zone in ways we currently do not fathom, motivating further study of the problem. We basically want to answer three questions: Where in subducting crust do the series of reactions transforming basalt/gabbro to eclogite and attendant dehydration occur? This question is important because it dictates where the large volume change of that transformation (-15%) occurs and this volume change must be accommodated by slab deformation. What are the quantitative effects of these reactions on the states of stress of subducting slabs and in particular where is the locus of maximum seismic moment release? Are slab seismicity, velocity structure and focal mechanisms consistent with a phase
change model of slab deformation? The first question is best addressed by experimental studies of the kinetics of mafic metamorphic reactions. The second question is best studied by numerical simulations of the stresses that accompany the volume changes of such reactions and studies of slab seismicity and focal mechanisms. The third may be answered by examining the seismicity and focal mechanisms of active subduction zones. The range of expertise required to answer these questions is not found in any one project and hence it benefits from collaboration with other projects in two other branches: BIVP (S. Bohlen and R. Denlinger) and BSGI (E.R. Engdahl). It also benefits from cooperative support from the Deep Continental Studies Program.

Results:

Experimental Studies. We undertook two important tasks in our exploratory program on experimental kinetics of transformations in mafic minerals. First, we are adapting the ultrasonic technique for in situ detection of mineral reactions to the piston-cylinder, the apparatus that can reach transformation pressures in mafic systems. This technique detects changes in time of flight of a pulse echo from an ultrasonic source located on one end of a sample and reflecting off the other end. A reduction in time of flight should result from the shortening of the sample that accompanies the volume change and from the increase in the ultrasonic velocity of the higher-pressure phases. We have built the instrument package with its computer interface and are working on reducing the complexity of the ultrasonic waveforms and reducing the signal-to-noise ratio by improving the assembly design. When the design is optimized, we can establish a complete reaction curve from a single computer-automated experiment. With a series of such experiments at different pressures and temperatures, we can efficiently determine kinetic laws. Second, Brad Hacker has completed his exploratory study of the albite → jadeite + quartz reaction, a model reaction for one of the key steps in the formation of eclogite: the consumption of the albite component of plagioclase to produce omphacitic clinopyroxene and quartz (Hacker et al., 1993). He confirmed preliminary findings reported last year that excess water reduces the temperature required to induce significant reaction from 1100°C under dry conditions to 700°C with water added. The optical transformation microstructures are also markedly different in specimens reacted under wet and dry conditions (Hacker et al., 1992, 1993; Bohlen et al., 1992, 1993). These results buttress our argument that large-scale eclogite formation in slabs coincides with slab dehydration. In thermally-mature subduction zones, the prevailing theory from petrology is that this takes place at the roots of arc volcanoes.

Theoretical Studies. Denlinger and Kirby have completed an initial 2-D finite-element model of stress state in a 50 km-thick flat plate with a total down-dip length of 200 km. A 5-km-thick crust transforms to eclogite with a volume
reduction of 12%. No slip occurs along the crust-mantle boundary. Both elastic and simple plastic rheologies were adopted. The difference in computed stress levels for these two rheologies is proportional to the amount of plastic deformation. The assumed yield stress does not change the pattern of deformation, which is dominated by in-slab stretching in transformed crust that decays rapidly updip from the gabbro/eclogite phase boundary. In the mantle beneath the crust-mantle boundary, both compressive and stretching deformations are produced. We have also investigated the energetics of these slab stresses based on thermodynamic constraints that require that the elastic strain energy can only be nonzero when the transformation occurs under disequilibrium conditions, i.e., at depths greater than the equilibrium P-T mineral reaction boundaries. This means that the onset of these phase-change stresses with depth be no shallower than the equilibrium boundary of the shallowest eclogite-forming reaction, that producing garnet at pressures of 0.8 to 1.4 GPa at 600°C. Those pressures correspond to depths of 20 to 45 km, an interval that brackets the depth of onset of non-flexural intraslab earthquakes in subduction zones involving young, hot crust, such as Cascadia, Southern Mexico and Southern Chile.

Seismic Studies. In an effort to gain insight into the pressure, temperature and stress conditions found in subducting lithosphere, we have conducted a preliminary study of the seismicity and focal mechanisms of subduction zones as a function of the age of lithosphere entering trenches. We used ISC and Harvard CMT data. The results of our study show clear and marked changes in earthquake depth distribution, focal mechanisms and maximum moments with increasing age of lithosphere up to plate age of about 20 Ma (Table 1). At greater age, no significant changes occur in intermediate-depth seismicity. The changes in

<table>
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<tr>
<th>Table 1 Plate-Age-Dependent Properties of Intermediate-Depth Intraslab Earthquakes in Subduction Zones</th>
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<tr>
<td>Maximum Earthquake Depth</td>
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<tr>
<td>Depth to Onset of Non-flexure EQs</td>
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<tr>
<td>Depth to First Peak in EQ Numbers</td>
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<tr>
<td>Maximum Seismic Moment, M_0</td>
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<tr>
<td>Focal Mechanism Type</td>
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<tr>
<td>Examples:</td>
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<tr>
<td>Arc Volcanism</td>
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<td>Average Offshore Heatflow</td>
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*Table References*

a Earthquake of 15 January 1931 at 40 km depth in Southern Mexico (Singh et al., 1985)
Earthquake of 9 Dec 50 at 90 to 130 km depth in Northern Chile and Northwestern Argentina (Kausel and Campos, 1992; Okal, 1992)

Cascadia (Juan de Fuca: 2.6-9.4 Ma), Southern Mexico (Cocos -102 to -95°E: 3-17 Ma), Central Mexico (Rivera -104.5 to -107° E: 7 to 15 Ma); Colombia/Ecuador (Nazca 1 to 3.5°N: 12-15 Ma), Central Manila (Eurasia 16-18°N: 15.5 to 20 Ma) and Nankaido (Philippine: 20-22 Ma). Very sparse shallow slab seismicity was also found in the South Shetlands (Antarctic: 16-21 Ma), Southern Chile (Nazca -42 to 47°N: 0-11 Ma), and Tierra del Fuego (-47 to -55°N Antarctic 10-20 Ma).

South America -42 to 1°N, Central America, Vanuatu, Northern Ryukyu, Taiwan, Northern Philippines, Southern Alaska and the Aleutians.

seismic characteristics with plate age up to 20 Ma parallel those of heat flow and arc volcano vigor and suggests that slab thermal structure has a strongly nonlinear effect on slab stresses and/or seismic failure processes and how they vary with depth. The temperature effect on the kinetics of metamorphic reactions has the requisite nonlinear form.

We collaborated with Bob Engdahl of BSGI in Golden in interpreting precise relocations of slab earthquakes. Engdahl's reidentified the associated phases reported to the ISC in South and Central America. He distinguished between depth phases (especially pP vs pwP) and core phases with crossovers in travel time by predicting the bounce points and the local depth to the ocean floor and then fitting the observed travel-time data of associated phases to the predicted travel-time curves for all phases (van der Hilst et al., 1991; van der Hilst and Engdahl, 1992). Moreover, he passed the resulting solutions through a quality filter based on maximum standard errors of the solutions and a minimum azimuthal station coverage. A significant result of the cooperative work with Bob Engdahl was the discovery of numerous curvilinear clusters of intermediate-depth earthquakes in the subducting Nazca slab, some of which are aligned with offshore seamount and island chains and the orientations of all of them are consistent with Cenozoic motion of Nazca relative to the hot-spot reference frame (Kirby and Engdahl, 1993). These clusters are, by this evidence, the seismic expressions of subducted volcanic features that were formerly island-and-seamount chains. We are testing an extension of the model of Kirby, Denlinger, Hacker and Bohlen (in preparation) that these regions of clustering represent the effects of dehydration and eclogite formation on the stress state and failure in subducting crust that is locally anomalously thick. Evidently, thicker crust delays the progress of these metamorphic reactions to depths greater than 100 to 150 km and hence intense seismic activity extends to those depths. Globally, much of the seismic moment at depths between 150 and 325 km is released in clusters of this type and it is significant that subduction zones which have little complexity in the crustal structure being consumed at trenches (e.g., the Kuriles and the Central Aleutians)
also do not show earthquake clustering in that depth range. This connection between subducting volcanic features and seismic moment release at intermediate depths may be a significant tool in assessing the zonation of seismic risk from those earthquakes, providing that we know something about the complexity of crustal structure and recent subduction history as recorded in forearc deformation. A similar connection between volcanic edifices on the ocean floor and subduction-zone earthquakes has been raised by Mark Cloos (1992) who points out that some large underthrusting earthquakes may represent the dismemberment of such edifices by interplate underthrusting. It is significant that many of the medium-sized linear volcanic edifices subducting at the Peru-Chile trench produce clusters both at shallow and intermediate depths (Kirby and Engdahl, 1993).

Our final accomplishment is the organization and successful funding of an interdisciplinary conference on subduction called SUBCON: Subduction from Top to Bottom. The conveners were Kirby, Dave Scholl and Gray Bebout. Funding was made possible by writing six proposals to six Geologic Division Programs and outside funding agencies. Our goal is to try to understand the diversity of the seismic expression of subduction by better appreciating the diversity of mineralogical and geochemical makeup and internal thermal and mechanical structure of the subducting oceanic lithosphere entering trenches and by better understanding the evolution of oceanic lithosphere during descent. To accomplish this goal we have invited 126 scientists from varied backgrounds to spend a week with us at a multidisciplinary conference on Catalina Island in June of 1994. They have been asked to convey their science in terms intelligible to the other scientists at the meeting. This may well be the first time such a breadth of expertise has been brought together to focus on what is clearly a very complex thermal/chemical/mechanical environment.

References Cited (but not in section that follows)
Reports Published (Late 1992 to end of 1993):

Papers


Abstracts


Investigation of Anza Seismic Network Data for Fault Zone Trapped Waves

14-34-93-G-2289
Program Element 1.1

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INVESTIGATION

Our investigation has two main objectives: to search for evidence for fault zone trapped waves at the locked segment of the San Jacinto fault (SJF) near Anza, California and to evaluate detailed fault zone structures of the SJF Anza segment using trapped mode data.

Small earthquake epicenters near Anza seismic slip gap define a 20 km quiescent segment of the SJF bounded to the northwest and southeast by areas of relatively high seismicity. Since 1890 at least six and perhaps as many as 10 earthquakes greater than M6 were associated with the SJF. The 1899 M6.4, 1918 M6.8, 1923 M6.2, 1937 M6.0, 1942 M6.5, 1954 M6.2 and 1968 M6.8 earthquakes occurred the edges of the Anza gap. Smaller more recent events such as the 1967 M4.8 and M4.7, 1975 M4.8, 1980 M5.5 earthquakes occurred in the region of the Anza seismic gap (Figure 1). A 12 mm/year surface slip rate in late Pleistocene-Holocene is also measured in the Anza section. Based on a seismic gap in the rupture zones of past M=6 shocks, the Anza segment has been proposed as a likely rupture plane for a M6+ earthquake.

In the present investigation, we use fault zone trapped waves to study the fault zone structure in 3-D at the Anza segment and the probable nucleation process of a future main shock. Because the characteristics of fault zone trapped waves (amplitudes and frequency contents) are strongly dependent on the locations of the sources and receivers relative to the fault zone, we can resolve the fault zone core layer (fault gouge) with thicknesses from tens to
hundreds of meters. We can probably distinguish microevents that occur in the immediate vicinity of the fault plane. These events are far more relevant to the nucleation process of the mainshock than the more numerous events occurring at the flanks of the fault zone.

RESULTS

In phase I of this investigation, we deployed five portable REFTEK instruments with nine three-component sensors at three recording places along the surface trace of the SJF Anza segment for four months in 1992 (Figure 1). Two places (called REF1 and REF2) are near station WMC of the USGS/UCSD Anza Seismic Network and the third one (REF3) is near network station SND. We recorded about 300 seismic events. In phase II, we reoccupied the recording place REF3 and deployed six REFTEK stations along a 500 m line perpendicular to the fault trace in 1993. We recorded forty events in three weeks. Figure 2 shows epicenters of 120 events recorded by REFTEK instruments with appropriate data quality for waveform analysis.

We completed a systematic examination of these events in the time and frequency domains. We found distinct wavetrains with relatively large amplitude and slight dispersion, closely following S-waves (Figure 3). These wavetrains show up only when both the stations and the earthquakes are close to the fault trace. We interpret these wavetrains as seismic guided waves trapped in a low velocity fault zone. Based on trapped mode data recorded by portable instruments, we examined the recordings of the Anza seismic network for these events. We found that the fault zone trapped waves were registered only at station SND which is located closest (~100 m south) to the fault trace. Also, we did not observe trapped waves at any stations for earthquakes occurring outside of the fault zone.

To confirm the existence of fault zone trapped waves, we eliminated source and recording site effects by the coda normalization method. The normalized amplitudes of fault zone trapped waves show a spectral peak at 3-5 Hz for events occurring within the fault zone southeast of the Anza gap. A spectral peak at 5-8 Hz is found for events occurring within the fault zone near the gap to the northwest. Interestingly, similar fault zone trapped modes were also found at the San Andreas fault (SAF) near Parkfield (Li et al., 1990) and recently at the fault zone ruptured in the Landers, California, earthquake of 1992 (Li et al., 1993). But, the dominant frequency of trapped waves at the SJF Anza segment is higher than the dominant frequency (2-5 Hz) of trapped waves at the SAF near
Parkfield or at the Landers fault zone. This implies that the width of the fault zone at Anza gap is narrow and/or the velocity contrast between the fault zone and surrounding rocks is low. Figure 4 shows the synthetic SH-component of fault zone trapped waves using the 2-D finite difference method (Vidale et al, 1985). By modeling of trapped waves, we estimate that the width of the low velocity fault zone is about 150 m southeast of the Anza gap and narrows to less than 100 m in the gap itself. The shear velocity is about 2.5 km/s for the fault zone and 3.5 km/s for the surrounding rocks. We shall do more thorough modeling of trapped waves that should result in a more detailed 3-D model of the fault zone.

Hypocenters of earthquakes with clear fault zone trapped waves (denoted by the filled symbols in Figure 2) show a systematic distribution both laterally and with depth, delineating the extent of the low velocity fault zone along the SJF trace in three dimensions. We find that the low velocity fault zone extends to a depth of at least 15 km. This zone is well developed along the Coyote Creek fault (south branch of the SJF) southeast of the Anza where the M6.0 earthquake of 1937 and the M6.8 Borrego Mountain earthquake of 1968 occurred. The zone also exists along the middle branch of the SJF between Anza and Clark Valley, but extends a short distance (10-15 km) along the Buck Ridge fault (north branch of the SJF). The hypocentral distribution of the events also suggests that the Coyote Creek fault may dip to northeast at an angle of ~75°, and merge into the SJF at a depth of ~15 km, consisting with the results from seismotectonic study (Sanders and Kanamori, 1984). We also find that this zone exists northwest of the Anza gap along the San Jacinto Valley segment (middle branch of the SJF) but is not well developed along the Casa Loma fault (south branch of the SJF) and the Hot Spring fault (north branch of the SJF). This implication from fault zone trapped mode data is consistent with the seismicity analysis at the Anza segment (Magistrale and Sanders, 1993). This also suggests that the San Jacinto Valley fault might be ruptured in the 1899 M6.4 and 1918 M6.8 earthquakes instead of the Casa Loma fault.

We continue the analysis of the entire Anza Seismic Network data set since 1982 for further evidence for the interpretations addressed above.

PUBLICATIONS AND REPORTS

Li, Y. G., K. Aki, T. L. Teng, F. L. Veron, Observations of fault zone trapped waves at the San Jacinto fault near Anza and at the San Andreas fault, Lonepine Canyon, southern California, IRIS Meeting, Hawii, 1993.


Li, Y. G. and F. L. Vernon, Fault zone trapped wave observations and implications on locked segment of the San Jacinto fault near Anza, California, in preparation.
Figure 3 Three-component seismograms recorded at Anza network station FRD (top) and SND (bottom) for an earthquake occurring within the Coyote Creek fault. The fault zone trapped waves are observed at SND that is located close to the surface trace of the SJF but are not registered at FRD that is located with a large offset from the fault trace.
Figure 1 Location map of REFTEK stations (REF1, REF2, REF3 denoted by solid bars) and stations of the Anza Seismic Network (denoted by squares). The epicenters of major earthquakes with $M>4$ since 1890 are denoted by solid circles.

Figure 2 Epicenters of earthquakes recorded by REFTEK instruments in our investigation. The magnitudes and depths of events are classified by different symbols as shown at the right. The filled symbols denote events with clear fault zone trapped waves.
Figure 3 (continued) Three-component seismograms recorded at Anza network station SND (top) and REF3 station (bottom) for an earthquake occurring within the fault zone.

Figure 4 Synthetic SH-type fault zone trapped waves for a 21-station array across the fault zone for comparison with observations in Figure 3. The middle trace corresponds to the station located at the fault trace. The station spacing is 20 m.
Source parameters of the 1992 Joshua Tree earthquake sequence are being examined from broadband regional TERRAscope data and from local recordings by Southern California Earthquake Center portable, digital instruments. In order to calculate source parameters, non-linear least-squares best fits are calculated to P-wave spectral ratios. At each site the main shock Fourier amplitude spectrum is divided by the foreshock and aftershock Fourier amplitude spectra. Spectral ratios are used instead of the spectra because the division of the spectra of colocated earthquakes should remove site and path effects leaving only the divided source spectra. In this study the spectral ratios are fit to a source model from Boatwright [1978]. This spectral source model is similar to earthquake source models originally proposed by Aki [1967] and Brune [1970].

\[ R(f) = \frac{\Omega^L_0 \left[ 1 + \left( \frac{f}{f^S_c} \right)^{2\gamma} \right]^{1/2}}{\Omega^S_0 \left[ 1 + \left( \frac{f}{f^L_c} \right)^{2\gamma} \right]^{1/2}} \]  

\( R(f) \) is the ratio of the Fourier amplitude spectra. \( \Omega^L_0 \) is the low-frequency spectral asymptote of the Joshua Tree main shock spectrum (larger earthquake) and \( \Omega^S_0 \) is the low-frequency spectral asymptote of the foreshock or aftershock spectrum (smaller earthquake). Similarly, \( f^L_c \) and \( f^S_c \) are the corner frequencies of the main shock and foreshock/aftershocks, respectively. The parameter \( \gamma \) is the source spectral falloff which is assumed to be 2.0.

The fit parameters are the ratios of the low frequency asymptotes, \( \frac{\Omega^L_0}{\Omega^S_0} \), and the corner frequencies \( f^L_c \) and \( f^S_c \). The ratio of the low frequency asymptotes is equal to the ratio of the seismic moments for colocated earthquakes with the same focal mechanisms. The spectral ratios at each of the TERRAscope sites are jointly inverted for the corner frequency of the main shock (fixed to be the same for all spectral ratios), the corner frequencies of the smaller earthquakes (foreshock and aftershocks), and the seismic moment ratios.

The least-squares best fits are determined by iteration from an initial guess using the simplex algorithm [Nelder and Mead, 1965; Caceci and Cacheris, 1984]. An example of a fit to a spectral ratio from site PAS is shown in Figure 1.

The stress drop can be estimated from the seismic moment and the S-wave corner frequency [Brune, 1970].

\[ \Delta \tau = \frac{7}{16} \left( \frac{2\pi f_c}{2.34} \right)^3 M_0 \]  

where \( \Delta \tau \) is the stress drop, \( f_c \) is the S-wave corner frequency, \( \beta \) is the shear wave velocity at the source, and \( M_0 \) is the seismic moment. The shear wave velocity is assumed to be 3.3 km/s. In the
present study, the P-wave corner frequency is used instead of the S-wave corner frequency. In order to use equation (2), the P-wave corner frequency is assumed to be 1.46 greater than the S-wave corner frequency following Trifunac [1972].

Results

Seismic moments, corner frequencies, and stress drops have been calculated for the main shock, its largest foreshock, and 12 aftershocks using recordings from TERRAscope stations (Figure 2). Seismic moments range from $2 \times 10^{21}$ to $2 \times 10^{25}$ dyne-cm. Corner frequencies range from 0.51 to 4.8 Hz. Aftershock stress drops range from 4.2 to 41 bars with a log-average stress drop of 15 bars. The foreshock stress drop is relatively large, 31 bars, but is within the aftershock stress drop range. The main shock stress drop of 203 bars is significantly larger than any of the aftershock or foreshock stress drops.

These results indicate that the main shock stress drop is significantly greater than the aftershock stress drops. There are several possible causes for the difference in the stress drop between the main shock and aftershocks. As suggested by Kanamori et al. [1993], the low stress drops of aftershocks compared to the main shock may be related to observations that short repeat time earthquakes have lower stress drops [Kanamori and Allen, 1986; Houston, 1990]. The lower stress drops for shorter repeat time earthquakes may be due to shorter healing times between ruptures. This explanation seems to imply that at least some of the aftershocks re-ruptured the rupture plane of the main shock.

Another possibility is that the main shock was a nearly complete stress drop event with aftershocks occurring on weak adjacent faults as was suggested for the 1989 Loma Prieta, California, earthquake [Beroza and Zoback, 1993; Zoback and Beroza, 1993]. The low aftershock stress drops may be an indication that the aftershocks are the result of relatively low residual stresses remaining after the main shock rupture. These residual stresses would be significantly less than the tectonic stress that was built up prior to the main shock.

The stress drop of the foreshock is somewhat more difficult to explain. Both the study of Kanamori et al. [1993] and the present study find the foreshock stress drop to be relatively large, but within the range of aftershock stress drops well below the main shock stress drop. Since the foreshock is the result of stresses in place prior to the main shock, it might be expected that the foreshock would have a stress drop close to the main shock stress drop. The foreshock may have occurred on a weaker section of the fault that dynamically loaded but could not rupture through a stronger section of the fault where the main shock nucleated. Regardless, since the foreshock stress drop is low compared to the main shock stress drop, it appears that it would have been difficult to identify the foreshock as a precursor to a larger earthquake from its stress drop alone.

REFERENCES:


Table 1. Source Parameters of the Joshua Tree Earthquake Sequence.

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<th>Earthquake</th>
<th>No. stations</th>
<th>Magnitude Caltech catalog</th>
<th>log-average moment (dyne-cm)</th>
<th>log-average corner frequency (Hz)</th>
<th>log-average stress drop (bars)</th>
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# The seismic moment of the Joshua Tree main shock is taken from Kanamori et al. [1993]. Seismic moments of the other earthquakes are determined from this value and the ratios of the low frequency asymptotes determined from the least squares fits.

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Figure 1. Example of fit to spectral ratio at station PAS for main shock spectrum divided by aftershock spectrum. Ratio of low-frequency asymptotes is approximately 650, main shock corner frequency is 0.23 Hz, and aftershock corner frequency is 1.1 Hz.

Figure 2. Log-average source parameters of the six TERRAscope stations. Straight lines are lines of constant stress drop. Square is the main shock, triangle the foreshock, and circles are aftershocks.
APPLICATION OF GROUND-PENETRATING RADAR TO INVESTIGATION OF NEAR-SURFACE FAULT PROPERTIES IN THE SAN FRANCISCO BAY REGION

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Program Element 1.1

Objectives

Ground penetrating radar (GPR) provides, in many geologic environments, very detailed images of near-surface earth structure beneath the GPR survey line. These images contain information similar to what would be observed on the wall of a trench cut vertically along the same line. Preliminary data in the San Francisco Bay region indicate that GPR images do correlate with existing trench observations, can be used to locate faults where they are buried or where their positions are not well known, and can identify previously unknown faults. GPR data potentially provide a valuable adjunct to trenching for studying the history of displacements of geologic units across faults, and extending trench data to depths greater than those to which trenching can be done.

Data Acquisition

In July of 1993, personnel from The University of Texas at Dallas conducted ground penetrating radar (GPR) surveys at a number of sites around San Francisco Bay. The sites were chosen in consultation with people at the USGS office in Menlo Park (Drs. M. Fisher, M.G. Bonilla, and E. Brabb) to allow investigation of a variety of geologic situations and to give control by collecting data at previously trenched sites.

GPR data were collected at five main locations:

1) near Olema, across the presumed trace of the 1906 event. Trench data were available. A second site was investigated at the suggestion of our Olema contact; this was about 3 km SE of the first, and is at the presumed maximum displacement of the 1906 event. Both sites yielded high quality data; the second one provided the best depth of penetration (> 40 m) of all sites at which data were collected.

2) near Millbrae, in the San Francisco watershed. Trench data were available at two sites across the San Andreas (ref. 95
Bonilla et al., 1978). Both of these yielded data in which the mapped faults appear as disturbed zones in the GPR data.

3) near Altamont Pass, Livermore. Trench data were available at two sites across the Greenville fault. GPR data were taken at one of them. The fault is not visible at shallow depths in the GPR data, probably because the clays present there do not produce sufficient lateral contrast in material properties. However, there is a series of structural truncations that correlate with the mapped fault location at 10-15 m depth.

4) near Pescadero, on the coast. Trench data were available at one site across the San Gregorio Fault. This was the only site at which no correlation with faults was visible in the GPR data. This failure is consistent with the large proportion of clays at the site and the conditions (water saturated, possibly with salt water); both of these limit GPR penetration as they correspond to high electrical conductivity.

5) at the Freemont City Hall. Trench data were available at numerous sites around the city hall across the Hayward fault. GPR data were collected at two recent (1990) and three older (1986) trenches. The faults were visible in the GPR data and correlated with the mapped locations in the trenches.

Data Presentation

Preliminary results, in the form of plotted sections of all the data were presented and discussed upon completion of the field work, at Menlo Park and Deer Creek facilities of the USGS. This also produced initial discussions of possible future projects (e.g. landslides, as well as additional hazard and neotectonic applications).

Data Processing and Analysis

Data processing is now in progress; one PhD graduate student (Jun Cai) is spending 100% of his time on this project. Processing includes filtering, editing, adding topographic data, velocity analysis, migration and coherency enhancement. We expect to have a paper completed for publication in the spring of 1994, and will be submitting a follow-up proposal, for more GPR work in the Bay region, to NEHRP at that time.
Data format and availability
---------------------------------

Field data are in the format designed by the equipment manufacturer (Sensors & Software, Inc.). This consists of a file header containing survey parameter information, followed by each trace; each trace has its own header followed by the data samples in 16 bit integers. Field data are available from the P.I. at

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Edited data and plotted sections will be delivered to the USGS as part of the final project report, early next year.
Investigations

This project provides machine shop services for laboratory experiments in rock mechanics and for specialized experimental field equipment and instrumentation.

Results

The shop serves both the Branch of Earthquake Geology and Geophysics, and the Branch of Seismology. The in-house development and model fabrication capability provided by the machine shop is critically important to the overall efficiency of laboratory and field experimental efforts within the office. The skilled technical staff of the shop works directly with scientists on unique and untested experimental projects in an interactive mode. This close communication and iterative developmental process is difficult or impossible to achieve with a contracted approach. Furthermore, we believe the machine shop is cost effective given the typical volume of work in supporting the two branches. During the occasional but infrequent slack periods in developmental work, the shop can take on limited production machining that ordinarily would be contracted out, thus realizing further savings. Most material costs are borne by the projects requesting the work.

Reports

n/a
Array Studies of Seismicity
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Investigations

1. Data management for the Northern California Seismic Network (NCSN).
2. Prototype development of GIS-based seismicity maps.
5. Seismicity of the Calaveras fault.
6. Examination of seismic moment release rates in the Western U.S.

Results

1. The last phase of the reprocessing of NCSN earthquake data collected since 1968 was completed (see previous Reports). David Oppenheimer and Nan MacGregor-Scott identified likely explosions in the catalog using criteria of known quarry locations, time-of-day, day-of-week, date-of-operation, depth, and percent of compressional first-motion readings. They also fixed the origin coordinates of NTS blasts and seismic reflection/refraction explosions that were captured by the NCSN.

The entire catalog of earthquake locations, parametric data (e.g., phase readings, coda durations, etc.), and focal mechanisms now resides at the UC Berkeley/USGS data center and is available to users with access to the Internet. This project updates the data at the data center on a daily basis after processing by Barry Hirshorn. Waveform data since 1984 continues to be loaded onto the mass storage device at the data center. In addition, David Oppenheimer produced a network bulletin that documents station locations, location procedures, network response, and significant seismicity recorded by the NCSN during 1992.

Steve Walter prepares and distributes a report of seismicity recorded by the NCSN each week. This report is sent by e-mail and fax to more than 400 recipients, including the media, emergency response officials, government agencies, and academicians. The report is also posted to public access bulletin boards read by thousands of individuals. The report is a regular feature in many newspapers in California and is also distributed by a commercial enterprise. Nan MacGregor-Scott provides a daily telephone message of significant seismicity in the preceding 24 hours.
2. Because the catalog of earthquakes recorded by the CALNET between 1967 and 1992 now exceeds 320,000 earthquakes, with each year adding an additional 15,000 earthquakes, it is no longer practical nor desirable to publish bulletins of all earthquakes recorded by the network. Instead, most seismologists prefer to have the data in digital form. However, for the non-seismologist, there is a need for maps of earthquakes recorded by the network. To address this need, Steve Walter has generated raster-scan images of the 1:250,000 scale USGS topographic base maps for central California and has imported these scans into ARC/INFO, a GIS system that makes it possible to overlay the seismicity on the digitized topographic base. The resulting map series will have the same scale and boundaries as the maps of the Geologic Atlas of California published by C.D.M.G.

The San Jose sheet is our prototype map. For the map view, Steve has succeeded in portraying seismicity such that its color is a function of earthquake depth. Well constrained focal mechanisms are also depicted in map view. For the cross sections, we portray each aftershock sequence with its own color and make the color shade a function of the time of each event relative to the mainshock occurrence. Thus, it is possible to recognize both individual earthquake sequences and their time dependent aftershock behavior. We anticipate completion of this map by mid year and are at work on the adjacent San Francisco sheet.

3. Alex Bittenbinder successfully designed and implemented a prototype computer system that replaces the Real Time (Earthquake) Pickers (RTP) that have been operating continuously since 1981. The new generation of hardware uses multiple computers (PC’s running DOS and Unix machines) connected by Ethernet to digitize, detect, and locate earthquakes in real time. This project has been responsible for all of the hardware development and most of the software development. The code that times (picks) the earthquake arrival time was written by Will Kohler. Modifications to the time code reader were made by Lynn Dietz, and Barbara Bogaert managed the project flow.

The new RTP has three principal modules. The first module is the data acquisition computer. This machine digitizes 256 channels of analog seismic data at 100 sps in real time while simultaneously reading time code, checking for channel skipping in the A/D, and broadcasting the time-stamped data onto an Ethernet cable for reception by the ‘picker’ module.

The ‘picker’ computer receives the Ethernet broadcasts of 256 channels of data in real time while simultaneously calculating the arrival time, first motion, and coda duration of any detected earthquakes. The picker module, at present, broadcasts its picks via RS232 to the locator module.

This third machine runs a prototype pick associator developed by Carl Johnson of the University of Hawaii at Hilo. The associator distinguishes earthquakes from independent noise triggers and reports earthquake picks to existing Unix software that locates the event and issues an alarm if the event meets prescribed criteria.

The project has also developing a module that displays selected channels of the real time data stream. This module is useful for network maintenance and debugging purposes. Q/A testing of all the modules is now underway and a documentation is being produced. We anticipate designing additional modules that attach to the Ethernet to save triggered waveform data, produce the average amplitude at each station over 1 second intervals for map display, and compute real-time amplitude spectral elements for detection of volcanic tremor.
4. Oppenheimer led an effort to publish an overview article of the Cape Mendocino earthquake sequence. See the Volume XXXIV report for a description on the seismicity recorded by the NCSN. Marian Magee has developed a 1-D velocity model for the triple junction region using a comprehensive set of stations and earthquakes spanning the period 1975 through 1993. This velocity model, derived through an inversion of traveltime data, will serve for as the basis of a detailed investigation of the seismotectonics of the region this year.

5. On 1/16/93 a M5.0 earthquake occurred on the Calaveras fault near Gilroy, California. An earthquake of this size was forecast for this location by Oppenheimer in a paper published in 1990, and the occurrence of this 1993 earthquake provides an opportunity to verify the forecast method. The earthquake occurred on the southeastern edge of a regions of the fault where persistent background seismicity occurred. It apparently ruptured to the south based on the pulse width pattern recorded at NCSN stations throughout the region and rupture was likely arrested by a pronounced right-step in the fault structure.

A similar sized earthquake occurred in this vicinity on 3/9/49. In collaboration with Doug Dreger of UC Berkeley, we digitized Wood Anderson, Bosch Omori, and Wiechert recordings of the 1949 earthquake for comparison with recordings made by broad band instruments now operating at similar locations. At the Mt. Hamilton site the coda of the 1949 event (the body waves are unreadable) has almost the same amplitude as the coda of the 1993 event, and the phase of the coda is quite similar, though not identical, in the frequency range of 0.25 - 0.85 Hz, suggesting that the events occur within a few hundred meters of each other.

A companion analysis by Doug Dreger who inverted the Bosch Omori 1949 seismograms and the 1993 broadband seismograms recorded at Berkeley indicates that both events have the same focal mechanism, S-P time, and depth. However, the synthetic Bosch-Omori constructed from the 1993 record is similar, but not identical, to the 1949 record. Thus since 1897, this section of the Calaveras fault has had only two earthquakes at the M5 level. The radius of a circular crack for an earthquake of this size is approximately 1 km, suggesting that the remainder of the fault apparently slips primarily by creep and microseismicity over its seismogenic depth range of 10 km.

6. The relative role of block versus continuum deformation of continental lithosphere is a current subject of debate. In collaboration with Geoff King and Falk Amelung of the I.P.G. Strasbourg, we compare plate rates to seismic moment release rates in the western U.S. to show that about 60% of the Pacific - North American plate motion apparently occurs seismically and 40% aseismically. The San Francisco Bay area shows similar partitioning between seismic and aseismic deformation, but within the seismogenic range, aseismic deformation is concentrated near the surface and at depth. In some cases this deformation can be located on creeping surface faults, but elsewhere it is spread over a several kilometer wide zone around the fault. Our results support the dominant role of non-continuum deformation processes with the implication that deformation localization by strain-softening occurs in the lower crust and probably the upper mantle.

Reports


Physical Basis for Seismicity Associated with the Earthquake Cycle and Development of Asperities (grant 14-08-0001-G2276)

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Program element: 1.2

Investigations:

1.1 Theoretical modeling of earthquake ruptures, recurrence, and asperity development, considering lab-based friction, pore pressure and elastodynamic effects.

1.2 Stress transfers during the earthquake cycle in oblique subduction segments and associations between asperity induced stressing and seismically active areas of the outer rise.

Results:

2.1 Theoretical modeling of seismic response is being done in relation to lab-based frictional or rheological material properties and to geometric disorder of fault zones, to understand factors affecting rupture mode, recurrence, spatio-temporal complexity of slip and seismicity, and development of slip-deficient asperity regions. Most of the modeling has been done in a quasistatic manner, with a radiation damping term, a feature of exact elastodynamics, included to allow solutions to exist during instabilities (Rice, 1993a). We have also begun some exact elastodynamic analyses (Perrin and Rice, 1993, Rice, 1993b, c), thus far in anti-plane strain, within the same rate- and state-dependent frictional framework. Elements of progress are as follows:

2.1.1 The modeling of recurrent earthquakes, covering time periods of hundreds to thousands of years and 3D elastic stress interactions, is computer-time limited. An new and fully explicit numerical algorithm has now been developed which, according to 2D test cases, is a factor of 10 to 20 times faster than the implicit algorithm (Rice, 1993a) we have previously used. We are still programming and de-bugging the fully 3D version. This explicit algorithm works because of the presence of the radiation damping term in the "quasistatic" formulation. Regarding slip $\delta$ and stress $\tau$ as variables, and $i$ as an index of points in the computational grid, elasticity considerations for a fault forced to slip at a time-average rate $V_{pl}$ require that

$$\tau_i = \tau_i^0 - \sum_j K_{ij} (\delta_j - V_{pl} t) - \left( \mu / 2 c_s \right) d\delta_i / dt$$

where $K_{ij}$ are the elastic stiffnesses, which scale as shear modulus $\mu$ divided by grid spacing, and $c_s$ is the shear wave speed. This equation set is complemented by a constitutive law relating each $\tau$ to the corresponding $d\delta/dt$ and prior $\delta$ history. The algorithm solves the two equation sets simultaneously for $\tau$ and $d\delta/dt$ at each time step. An advantage of this approach is that it has the same structure as our algorithm for the exact, fully elastodynamic analyses; in those the
multiplication by a stiffness matrix above is replaced by a convolution over time,

\[ \sum_j K_{ij} \delta_j(t) \rightarrow \sum_j \int_{-\infty}^{t - \text{Travel Time (i, j)}} \hat{K}_{ij}(t - t') \frac{d\delta_j(t')}{dt'} dt'. \]

This similarity in program structure should ease the transition to a future version that includes full elastodynamic treatment during instabilities; the additional coding steps and storage needed are those to carry out the convolution on time.

2.1.2 The program for treatment of recurrent earthquakes has also been broadened to allow choice from a set of constitutive responses, and the new explicit procedure allows easy addition of new forms. Rate- and state-dependent friction can be modeled with the familiar Ruina-Dieterich "slip" law used in our prior work, or with the Dieterich-Ruina "slowness" law, and a modification recently suggested by Weeks to represent velocity strengthening in granite at higher slip rates can be included too. For the deeper and hotter parts of the fault zone, the net slip rate \( V \) can be chosen as the sum of a creep part, proportional to some power of \( \tau \), and a frictional part which relates to \( \tau \) and slip history by one of the rate- and state-dependent forms discussed above. Further, pore-pressure can be specified and an elementary model of Lachenbruch-Mase-Smith shear heating of the pore fluid is available too. These options have allowed study of the effects of assumptions concerning elevated pore-pressure, extreme velocity weakening in rapid slip, and shear heating, all of which could be consistent with low overall stress levels in major fault zones.

2.1.3 The full elastodynamic analyses are aimed at understanding the extent to which seismic complexity could be sustained by strong stress heterogeneities left by the wave-mediated arrest of seismic slip, even in the absence of geometric impediments to slip or of strong material heterogeneity. They have been carried out in anti-plane strain and covered only a limited range of material and fault system parameters and of loading methods. One series of calculations suddenly steps up the stress acting along the fault (or stress that would act, in absence of slip), in a way that the stress varies randomly with position, being large enough to induce slip at seismic rates at some positions but too low at others. The calculations are all carried out with velocity weakening friction laws that include a critical slip distance, typically called \( L \) or \( D_c \), for state transition, and with adequate refinement of the computational grid to properly represent the continuum limit of the governing system of equations. Results thus far have revealed no tendency for the heterogeneity of stress to be increased along the portion of the fault zone that ruptures dynamically (apart from the stress concentration at the arrested ends of the rupture), and in most cases the strong initial stress variations are smoothed to negligibly small fluctuations.

2.1.4 The elastodynamic analyses have also led to an understanding of what types of laws are consistent with the short duration slip pulses suggested by Heaton. We have derived necessary conditions for their existence as travelling wave elastodynamic solutions (slip depends on position \( x \) and time \( t \) only in the form \( x - V_r t \), where \( V_r \) = rupture velocity) and find the following: Such slip-pulse solutions do not exist when the frictional resistance, after initial rupture, is assumed to depend on slip rate only, i.e., without any dependence on slip or on the evolving state of the surface. Such solutions also do not exist for versions of the rate- and state-dependent framework, like the Ruina-Dieterich "slip" law, which do not allow re-strengthening in truly stationary contact. Versions that do allow such strengthening, like the Dieterich-Ruina "slowness" law, are consistent
with the existence of pulse-like solutions, although these seem actually to exist only in parameter ranges for which that re-strengthening is relatively rapid. In terms of the parameters A and B which enter such friction laws, one seems to need B much larger than A; at least, we see such pulses in runs with A/B = 0.2 but not with A/B = 0.7.

2.2 Stress transfers during the earthquake cycle in oblique subduction segments have been studied. These transfers are between asperities along the interplate interface (zones of higher locking and high slip in large/great earthquakes) and outer-rise areas, adjacent to the rupture zones, as well as slab areas at intermediate depths, down-dip from the rupture zones. It has been shown previously in our work (Dmowska and Lovison, Tectonophysics, 1992) that locking of asperities during the cycle results in an uneven distribution of seismicity along strike, both in the outer-rise and at intermediate depth, with seismicity clustering next to asperities on the interplate interface. In subduction segments with direction of convergence approximately perpendicular to the trench (as, e.g., Alaska 1964, Valparaiso 1985) seismically active areas in the outer-rise and at intermediate depth are located next to asperities, along the direction of subduction. However, in study of oblique subduction segments in the western Aleutians (area of Rat Islands 1965 earthquake), we have found that the active areas of the outer-rise and of the slab at intermediate depth, associated with an asperity, locate next to asperities, but along directions somewhat between the convergence vector and the direction perpendicular to the trench. This is shown for the outer rise in Figure 1, which shows events with $m_b > 5.7$ occurring in the 22 year period afterwards, and also asperity locations from wavefield modeling by Beck and Christensen (JGR, 1991).

We have begun 3D finite element modeling of a subducting slab with asperity regions on the thrust interface (Dmowska et al, 1993; Zheng et al., 1993). The standard sawtooth slip history is imposed on the asperity, and the rest of the interface is allowed either a freely-slipping or viscous response. Stresses are calculated in the outer rise. Seismicity should be affected only where the trench-perpendicular extensional stresses, caused by the earthquake cycle, superpose on the bending stress field of the outer rise. In general we have found that the assumption of asperity shapes that are symmetric about an axis perpendicular to the trench cannot cause the locations of high cycle-related stresses to be displaced along strike as much as suggested by the observation in the top figure panel. However, assumption of asperity regions that are strung out along the path of oblique convergence, like in Figure 2 (and, speculatively, due to the wear debris of a subducting seamount), can cause the locations of highest stress to shift distances along strike comparable to those observed; contours of the trench-perpendicular extensional stress change caused by slip on the asperity are shown in Figure 3.

Reports:


Figure 1: Adapted from Dmowska and Lovison (*Tectonophys.*, 1992): Region of 4 February 1965 Rat Islands earthquake, Mw = 8.7. Subsequent outer rise events with mb > 5.7 shown for period up to 31 August 1987. Cross-hatched areas are asperity locations from Beck and Christensen (*J. Geophys. Res.*, 1991)
Figure 2. View onto thrust interface. Vertical axis: distance in km from trench; horizontal axis: distance in km along strike. Darkened region is an assumed asperity location.

Variations of Stress Component $\sigma_{11}$ (unit: $\sigma L/\mu TV\alpha$, $L = 80.0$ km)

$\sigma_{\text{max}} = 0.33E-1$  $\sigma_{\text{min}} = -0.87E-2$

Figure 3: Finite-element results (Zheng et al., 1993) showing contour lines of alteration in trench-perpendicular extensional stress along the surface of the earth following slip along the asperity. Vertical axis is distance from trench; negative range corresponds to subducting plate and its outer rise, positive to over-riding plate. When the asperity is assumed to be strung out along the oblique convergence direction, like in Figure 2, peak stress locations shift along strike a distance comparable to observed locations of the large outer rise events in Figure 1.
Quantitative Testing of Seismicity Pattern Hypotheses

# 1434-93-G-2283

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Program Element 1.2

Investigations

1. Test of the Remote Triggering Hypothesis for Central Asia Seismicity
2. Test of the "Extended" Mogi Hypothesis for Shallow/Deep Subduction Earthquakes
3. Some Implications of the Landers Case for Remote Triggering of Seismicity
4. Test of Remote Triggering of Seismicity for Western United States: the NEIC catalog

Results

Test of the Remote Triggering Hypothesis for Central Asia Seismicity

The unpredictable nature of earthquake occurrence can be explicitly stated as a null hypothesis: the temporal occurrence of earthquakes is random. Many investigators have searched for violations of this null hypothesis as the discovery of patterns within earthquake catalogs might ultimately help to predict future earthquake occurrence. Many seismicity patterns have been proposed. Most of these suggestions are based on qualitative inspections of seismicity maps. One interesting proposal is the remote earthquake triggering hypothesis; the passage of seismic waves from far-away earthquakes can trigger the initiation of an earthquake. Nikolaev and Vereshchagina (1991) presented a quantitative statistical analysis that supported remote earthquake triggering, delayed by 5 to 10 days, of Central Asian seismicity by earthquakes in the Pamir-Hindu Kush zone. We present an independent analysis of this specific hypothesis; our analysis includes: (1) comparison of the NEIC and ISC seismicity catalogs; (2) full consideration of the analysis technique; and (3) construction of synthetic seismicity catalogs based on the null hypothesis of random seismicity to determine the expected variations in occurrence frequency. We have shown that the claim by Nikolaev and Vereshchagina (1991) that quantitative analysis of Central Asian seismicity supports remote triggering must be rejected. In detail, the claim that Central Asian seismicity is higher 5 to 10 days after Pamir-Hindu Kush earthquakes is not seen in the different catalogs when analyzed by a more accurate technique. Furthermore, the observed variability in earthquake occurrence frequencies does not exceed the fluctuations expected from the null hypothesis that Central Asian earthquakes occur randomly as a function of time.

Test of the "Extended" Mogi Hypothesis for Shallow/Deep Subduction Earthquakes

Mogi proposed a hypothesis where great shallow earthquakes in the western Pacific region are preceded and sometimes followed by the marked increase of deep seismic
activity in the Wadati-Benioff zone perpendicular to the trend of the arc structure (Mogi, 1973, 1986). We test first the original hypothesis, i.e. just large earthquakes over the time scale of the 20th century (ABE catalog); and then test of an "extension" of the original hypothesis to smaller earthquakes (M≥4.5, NEIC catalog) and shorter time scales (from 1964 to 1988). We investigate all major subduction zones. The "master" events have M≥7.3 and occurred at the depths between 0 to 60 km. The "other" earthquakes have depths larger than 60 km and must occur within the box that extends ±600 km along the arc and extends for 1200 km downdip about the "master" event epicenter. Our tests do not support Mogi's hypothesis. Although we found some peculiarities in the earthquake frequency for Japan-Kurile-Kamchatka and Tonga-Kermadec zones, there are no common features for the seismicity in the different subduction zones.

Some Implications of the Landers Case for Remote Triggering of Seismicity

The 1992 Landers earthquake provided strong evidence for the remote triggering of seismicity (Hill et al., 1993, Science). The triggered seismicity consists of: (i) a temporary (one day to several days) increase in seismicity rate of small events; (ii) jump in detected seismicity from nothing to many events, and in some places; (iii) the occurrence of a large earthquake for that region. Hill et al. (1993) argue that the dynamic stress of the waves is the likely source of triggering; but the mechanisms in the source regions that connect the transient stress to triggered seismicity are more mysterious. The mechanisms can be crudely grouped into: (1) dynamic stress directly affects the process of frictional failure on the fault segments; and (2) dynamic stress affects some other crustal process, e.g. some fluid system, and the triggered process then eventually causes the seismicity. Given the tectonic setting of the triggered sites, Hill et al. (1993) and others have emphasized the role of mechanisms in category (2). In this paper, I shall focus on the direct effect of category (1). We start with a discussion of the most trivial model: each independent fault segment in a crustal volume has a stress state that is randomly assigned between σ0 and σ1, the earthquake occurs instantly when the stress reaches σ1. Then the likelihood that the fault segment will be triggered by transient stress σ_{dyn} is simply σ_{dyn}/(σ1-σ0). Applying the Gutenberg-Richter distribution to the independent fault segments, there are many fault segments that can produce micro-earthquakes, hence there can be a substantial number of triggered small events. On the other hand, the likelihood of triggering the one large earthquake in this region is simply σ_{dyn}/(σ1-σ0), which is 1% or less. A more complex statistical model allows for interaction and stress transfer. If we choose the practical maximum value for stress transfer from small to larger events, then the triggered micro-earthquakes can enhance the likelihood of the large event by about a factor of five or so. Thus, the preliminary conclusion is that the direct effect with stress transfer can explain most aspects of the triggered micro-seismicity, but triggering of the larger events in a region is unlikely from this simplest description of the "direct" mechanism. This justifies further investigation into more complex models of frictional failure or indirect methods of triggering.

Test of Remote Triggering of Seismicity for Western United States: the NEIC catalog

The Landers earthquake that occurred on June 28, 1992 triggered seismicity far beyond the aftershock zone at distances of up to 1250 km (Hill et al., 1993, Science). One of the proposed mechanisms of such triggering is the dynamic stresses associated with the passage of seismic waves, hence it is possible that triggering occurred after other large earthquakes in western North America. Our investigation quantitatively tests for the
presence of remote triggering in the NEIC seismicity catalog for the western part of North America. We test the remote triggering hypothesis against the null hypothesis that the occurrence time of remote earthquakes is random.

The area of investigation is bounded by 30° to 50° N and 100° to 130° W; there are 24 "master" events with M≥6.3. The addition of two "master" earthquakes that occurred in 1987 and 1988 in the Gulf of Alaska (M7.6) did not change any of the results. Explosions with M≤6.3 and aftershocks are eliminated. The total number of "other" events with M≥4.5 that occurred from January 1964 to December 1990 in the sub-catalog is 1004. Given results of Hill et al., we performed the tests with the earthquakes from San Andreas Fault zone excluded and included, but there is little difference in the results. We calculate earthquake occurrence frequency (eq/day) of "other" events in time bins (10 days each) after the "master" events. In comparison with fifty simulations of random seismicity, the observed seismicity produces an anomaly in the second bin (10 to 20 days after a large eq) with high confidence level, more than 4 sigma (see Figure 1, top). The 41 earthquakes in this bin occurred after 16 of 24 "master" events. More of than half the earthquakes in this bin occurred in the Mendocino-Juan de Fuca region: 23 of the 41 (see Figure 1, bottom). We divided all "master" events into 6 groups: 1- Nevada Test Site (NTS), 2-Imperial Valley, 3- Central California, 4- Mendocino-Juan de Fuca, 5-Vancouver Island, and 6- Idaho. We found that "master" events in all regions have been followed by "other" events in the 10 to 20 day bin. The other two anomalies that exceed the expected two-sigma fluctuation are in the first and sixth bins (to 10 days, and 50 to 60 days, respectively). Thus, the preliminary conclusion is that there is a statistical anomaly of higher earthquake occurrence frequency from 0 to 20 days after large events in western US. Preliminary tests show that this anomaly is not the result a single unusual sequence. Since the total number of "anomalous" (i.e., possibly "triggered") events is small (94 from 747), we need to perform further testing.

**Reports**

Related Papers:
Abstracts:
Figure 1 (top) Statistical test to determine the expected (one-sigma) fluctuations in earthquake occurrence frequency for the NEIC catalog for western U.S. Each box is ± one-sigma, based on the null hypothesis. (bottom) "Anomalous" (i.e., possibly "triggered") events occurred in the second bin (10 to 20 days after a large earthquake): 41 eqs occurred after 16 of 24 "master" events (diamonds). NTS - Nevada Test Site (8 of 24 "master" events are nuclear explosions).
We investigated four large earthquakes in Aleutian-Alaska-Cascadia region.

1. **The 1957 Aleutian Earthquake**
   The 1957 Aleutian earthquake had been estimated as the third largest earthquake this century (\(M_w = 9.1\)) and had the longest aftershock zone of any earthquake ever recorded-1200 km. However, due to a lack of high-quality seismic data, the actual source parameters for this earthquake had been poorly determined. We have examined all the available waveform data to determine the seismic moment, rupture area, and slip distribution. These data include body, surface and tsunami waves. Using body waves, we have estimated the duration of significant moment release as 4 min. From analysis of surface wave recorded at PTM, South Africa, we have estimated that significant moment release occurred only in the western half of the aftershock zone and that the best estimate for the seismic moment is 50-100x10^{20} Nm. Using the tsunami waveforms, we estimated the source area of the 1957 tsunami by backward propagation. The tsunami source area is smaller than the aftershock zone and is about 850 km long. This does not include the Unalaska Island area at the eastern end of the aftershock zone, making this area a possible seismic gap. We also inverted the tsunami waveforms to estimate the slip distribution. Again, slip on the 1957 rupture zone was highest in the western half near the epicenter. Little slip occurred in the eastern half. From this slip distribution, the seismic moment is estimated as 88x10^{20} Nm, or \(M_w=8.6\). Our slip distribution of 1957 Aleutian earthquake shows that the 1986 Andreanof Islands earthquake occurred in the area of major moment release of the 1957 rupture area; the 1986 earthquake represents a rerupturing of the major 1957 asperity.

2. **The 1938 Alaska Earthquake**
   Very little was known about the 1938 event; it seems to have ruptured the segment between the 1964 great Alaskan earthquake and the Shumagin gap segment. Most of the previous estimates of the seismic moment was through magnitude, not waveform modeling. We used tsunami waveforms recorded on 7 tide gauge stations and estimated the seismic moment of 20 x 10^{20} Nm (\(M_w=8.2\)). The rupture area is estimated as 300 km long along the trench, leaving the Shumagin gap segment as a seismic gap, and a large slip occurred in the eastern edge of the rupture area.

3. **The 1993 Shumagins Island Earthquake**
   An Ms 6.8 earthquake occurred on May 13, 1993, in the Shumagin seismic gap, which is an unbroken segment between the 1938 and 1946 earthquakes. We analyzed long-period surface waves and P waves recorded on the IRIS stations to estimate the fault parameters. The Centroid Moment Tensor solution shows that the focal mechanism is a thrust type with the strike parallel to the Aleutian trench. The seismic moment is 2.0 x 10^{19} Nm (\(M_w=6.8\)).
The Moment Tensor Rate Function inversion from P waves also yields a similar focal mechanism and seismic moment. In addition, this computation provides estimates of 10 s for the duration of the source time function and 35 km for the best point source depth. These seismological analyses indicate that the fault mechanism of the 1993 earthquake was as expected, but that the magnitude was too small to fill the gap. This earthquake did not generate a tsunami large enough to be observed at the Sand Point, Alaska, tide gauge or at an ocean bottom pressure gauge, at distances of 100 and 300 km, respectively. Numerical tsunami simulations result in amplitudes at both stations that are within the background noise level. Additional numerical experiments also suggest that the small tsunami amplitudes are due to the location of the source area in the shallow shelf region.

4. The 1992 Petrolia Earthquake

The April 25, 1992, Petrolia earthquake (Ms 7.1) occurred at the southern tip of the Cascadia subduction zone (CSZ). This is the largest thrust earthquake ever recorded instrumentally in CSZ. The mainshock was followed by two large aftershocks with strike-slip mechanism. Moment release of the mainshock and the two large aftershocks are 4.0 x 10^{19} Nm in the first 10 s, 0.7 x 10^{19} Nm in the first 8 s, and 0.9 x 10^{19} Nm in the first 2 s, respectively. The slip direction of the Petrolia earthquake was N80°E.

This slip direction cannot be explained by either the relative motion of the North American and the Juan De Fuca plates, N60°E, or between North America and the Gorda deformation zone (GDZ) N40°E. Prescott and Yu (1986) suggested that the North America-Pacific plate motion is accommodated by right lateral slip on both the San Andreas and Maacama-Rodgers Creek-Hayward-Calaveras fault systems; the intervening block is the Humboldt plate. If we modify the relative motion of the southernmost GDZ to conform with the seismicity trends and allow the Humboldt-Pacific plate motion to be about half the total North America-Pacific motion, then the GDZ-Humboldt relative motion matches the direction of the Petrolia slip vector. The Petrolia earthquake thus represents a subduction of the GDZ beneath the Humboldt plate. The mixture of focal mechanisms in the two distinct aftershock clusters can be explained by motion between the GDZ and Pacific plate, and the Humboldt and North America plates. Our study shows that the GDZ is subducting beneath the Humboldt plate in the Cape Mendocino area, and the Petrolia earthquake ruptured the entire subduction segment between the GDZ and Humboldt plate.

We also made tsunami computations from the Petrolia earthquake using the "best" fault model that explains the geodetic data and coastal uplift (Oppenheimer et al., 1993). The observed and computed tsunami waveforms are in fairly good agreements, indicating that the "best" fault model is also supported by tsunamis. One of the interesting, and important from a hazards point of view, observations of this relatively small tsunami is that the largest amplitude was observed a few hours after the initial tsunami arrival at most of the stations. Our computations also showed this feature, and suggests that the large later phases on tide gauges are as edge waves that propagated along shallow continental shelf. For evaluating tsunami potential from a possible great earthquake in the Cascadia Subduction Zone, it is important to include such large later phase, which might cause most damage.

5. References:


Reports:

1. Abstracts and Proceedings:


2. Papers:


Micromechanics of Rock Friction

Agreement No. USGS14-34-92 G2161
Program Element 1.1

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This is an experimental and theoretical study of rock friction in which the micromechanics of friction are studied by use of a model of the contact of random elastic surfaces.

In previous work the transition from partial to full sliding of the surfaces was studied. This takes place within the first 5-10 μm of sliding with the surfaces we study in the laboratory. Quantitative modeling show that this process can be well simulated with forward modeling based on measured topography of the experimental surfaces.

During the past year this has been extended through the stage of strong slip hardening until steady state friction is reached, in 0.1 to 1 mm of slip. To model this behavior we include the additional effects of oblique contacts (interlocking) and the evolution of surface topography during sliding (wear). This modeling successfully accounts for these later stages of friction and show that these processes account approximately equally to the additional friction that occurs after the onset of full sliding.

In order to facilitate the above study, an experimental study of the frictional wear of granite was also conducted. Modeling of the wear process allowed for the prediction of both transient and steady-state wear and the distinction to be made regarding the micromechanisms of ‘riding up’ and shearing through’ to be distinguished for oblique contacts.

Work has also been completed on scaling these processes to the geological scales, primarily through the scaling of the critical slip distance, D_c. We have also extended these studies to the second order frictional effects, that of slip velocity and variable normal load, and a manuscript reporting this is now in preparation.

Recent Publications

Three papers were completed under this grant, as of December 1993. Two have already been accepted for publication, while a third is under review. Below, I summarize some of the results contained in these papers.

"Prediction of Large Events on a Simple Dynamical Model of a Fault" [Pepke, Carlson, and Shaw, 1993] was accepted for publication in *Journal of Geophysical Research*. The paper presents results for long term and intermediate term prediction algorithms applied to a catalogue generated by the Burridge-Knopoff model. The idea in this paper is to study issues related to algorithm optimization and the intrinsic limitations of algorithms, in a situation where we have well controlled, intrinsically complex catalogues. The catalogues generated by the model are of arbitrary length, and arise from a model which is deterministically chaotic. Here, we seek not to show that any particular complex seismicity pattern generated by the model matches the Earth, but rather to study how algorithms based on intrinsically complex patterns work, and how algorithm optimization works on such catalogues. Some of our results are as follows.

One methodological question we address is the evaluation of the performance of a prediction algorithm. For this purpose, we introduce a linear cost-benefit function $Q$, which quantifies the tradeoffs that necessarily must be made between the different goals of the prediction scheme. It measures the extent to which an algorithm is able to fulfill all of the prediction goals ($Q = 1$) relative to the option of doing nothing at all ($Q = 0$). In the cases we consider, the goals are to predict the future event, with the alarm time on for as little time as possible, and with the minimum of false alarms.

As a benchmark for evaluating the results of the intermediate predictions, we first evaluated long term predictability. Three commonly used methods were examined: the time-predictable and slip-predictable models, as well as a prediction based on recurrence intervals. Neither the time-predictable nor the slip-predictable models described the behavior very well, though the time-predictable model did slightly better. Interestingly, for either the time or slip-predictable models, it was possible to find good correlation over just a few subsequent large events. At any point, however, such a short time “pattern” could be broken, with the next event differing dramatically from the proposed model.

Intermediate term prediction, based on individual precursor measures of the small event activity, produced forecasts with much smaller time windows than the long term predictors. Four predictors were considered. In order of best performance, they were active zone size, activity, rate of change of activity, and finally, fluctuations in activity, which did much worse than the other three.

Finally, we considered the effect of finite catalogue lengths. We measured the average and standard deviation of $Q$ as the catalogue length was increased. The average $Q$ rose rapidly to its maximum, and the standard deviation dropped rapidly to its minimum in less than a repeat time. This is relevant for the question of the stability of the learning process for algorithms. In the model, we find that catalogues containing one large event are sufficient
for stability in learning. If these results also apply in the Earth, one would expect continued improvement in algorithm performance as catalogue lengths reach the repeat times of large events, with a much slower improvement after that.

"Dynamics of Earthquake Faults" [Carlson, Langer, and Shaw, 1993] has been accepted for publication in *Reviews of Modern Physics*. In this paper, we review the variety of results that have been found concerning the behavior of homogeneous fault models with stick-slip friction and inertial dynamics. This paper was solicited by the editors, due to widespread interest in the physics community in the work our group has been doing on these fault models.

"Complexity in a Spatially Uniform Continuum Fault Model" [Shaw, 1993c] was completed and submitted for publication in Geophysical Research Letters. This paper addressed the question raised by Rice [JGR, 1993] of whether faults with a continuum limit could generate complex nonperiodic sequences. Here, I show that the introduction of a viscous term to the Burridge-Knopoff model provides a small lengthscale cutoff which allows a well defined continuum limit, and which continues to generate complex nonperiodic sequences. Thus spatial heterogeneity or inherent discreteness is shown to not be a necessary condition for complex sequences. Rice has shown that long range quasistatic interactions appear not to give complex sequences in the continuum limit; here I show that short range interactions with inertial dynamics do. The big question for seismology—what happens with both long range and fully dynamic interaction remains an open question.
Creep and Compaction within Fault Zones: An Explanation
Why Major Strike-Slip Faults Are Weak

# 1434-93-G2310

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Investigations

We have studied the physics of fault zones to determine why major strike-slip faults are weak. A basic observation which has motivated this work is that many strike-slip faults are weak both in a relative sense that the faults are poorly oriented with respect to the regional stress axes and in an absolute sense that the average frictional resistance is much less than expected from laboratory samples (Hickman, 1991; Zoback, 1991). These features are best documented for the San Andreas fault system. I begin discussion with the effective stress law for frictional failure

$$\tau_F = F (T_n - P_{\text{fluid}})$$

where $\tau_F$ is the shear traction at failure, $F$ is the coefficient of friction, $T_n$ is the normal traction on the fault, and $P_{\text{fluid}}$ is fluid pressure. The principal axis of compression is nearly normal to the fault (which implies high $T_n$) rather than the expected orientation for frictional failure about 60° from normal (Zoback, 1991). Seismic slip extends downward to around 20 km depth for the 1906 San Francisco earthquake (Matthews and Segall, 1993) and for the 1989 Loma Prieta earthquake (Lisowski et al., 1990). The lack of a detectable heat flow anomaly indicates that the average shear traction on the fault is less than 20 MPa (Lachenbruch and Sass, 1980; Hickman, 1991) while a coefficient of friction of 0.7 would imply 90 to 260 MPa of shear traction in the deeper part of the seismogenic zone between 7 and 20 km (200-570 MPa normal traction assuming "hydrostatic" fluid pressure in equilibrium with a column of water to the surface).

We have concentrated on a mechanism proposed by Sleep and Blanpied (1992) which produces transient fluid pressures. To explain this mechanism, it is necessary to distinguish frictional mechanisms which involve traction on a plane from "ductile" creep which involves molecular diffusion either within the pore fluid, for example, pressure solution, or within the grains, for example, linear or power-law creep. Most likely the grains themselves are brittle and the aggregate is ductile by pressure solution over long times and brittle over the duration of an earthquake. Under appropriate conditions, ductile creep can occur far below the criterion for frictional failure.

The basic physics of our mechanism are quite simple. Grains within the fault zone are stressed by the shear traction driving fault slip and the difference between lithostatic and fluid pressure. Ductile creep leads to compaction and fluid pressure increase because grains and grain-grain contacts within the fault zone cannot distinguish the two sources of stress. Frictional failure generates porosity in a low porosity rock—if you break something it does not fit back together. The continual difference between fluid and rock pressure and the episodicity of fault slip imply a cyclic variation in fluid pressure. Just after an earthquake, the fault zone is dilated and the fluid pressure is below hydrostatic. Creep gradually compacts the pore space increasing the fluid pressure above hydrostatic if the fault is sealed from its surroundings. Eventually increased pore pressure and increased shear traction lead to earthquake failure completing the cycle. That is, the earthquake then restores porosity so that little net gain or loss of fluid occurs from the fault zone and the fluid pressure is in long-term equilibrium with the country rock.
As summarized by Sleep and Blumhied (1992), there is extensive qualitative evidence from exhumed fault zones and laboratory experiments that these processes actually occur in the Earth. We thus concentrated on modeling the physical aspects of this mechanism. We have developed simple continuum physics models for ductile-brittle fault zone material within an elastic medium. We developed computer code to model a basic 1-D case analogous to a fault between two parallel plates. We also have modeled two-parallel fault splays, and a vertical fault whose properties depend only on depth. We have begun to investigate grain-scale processes that control the physics of fault zones. Two papers discussing our progress to date have been submitted to a special issue of Pure and Applied Geophysics on the behavior of fault zones and are currently in review.

**Results**

Our most important result is that fault zones have both macroscopic and grain-scale self-adjusting features that allow earthquake failure at low shear tractions. That is, minor amounts of ductile creep are sufficient to greatly increase fluid pressure and thus weaken the fault for earthquakes. Our mechanism has several attractive aspects. The laboratory coefficient of friction $=0.7$ holds in the Earth, and the time-averaged fluid pressure in a fault zone may be hydrostatic. The reality of the mechanism is suggested by laboratory experiments and studies of exposed fault zones. The macroscopic physics of the mechanism are simple and easy to model and the macroscopic rheology can be deduced from laboratory studies and grain-scale physics.

**Macroscopic models.** Macroscopic self-adjustment is illustrated by the 1-D models. For these simple conditions, behavior on the fault zone is periodic and therefore predictable. The fluid pressure in the fault zone adjusts so that it is in longterm equilibrium with the (hydrostatic) fluid pressure in the country rock. Acceptable models for shallow (Figure 1) and greater (Figure 2) depths were obtained by adjusting the viscosity of the fault zone.

This regular behavior disappears when additional complexity is added. Consider two parallel fault splays in a 1-D elastic medium (Figure 3). Earthquake failure on one splay reduces the shear traction on both but only the fluid pressure in the failed splay. Complex periodic or even apparently chaotic patterns of earthquake recurrence happen if the faults zones have different properties (Figure 4).

The simplest case that can actually occur in the Earth is a vertical fault zone whose properties depend only on depth. We have found that pore pressure changes associated with compaction are in themselves not sufficient to organize the fault so that individual depths of the fault fail together in large earthquakes. Rather, a slip-dependent friction (Rice, 1992) needs to be included in the code. We will attempt to find a practical way of doing this. (Slip-dependent friction models require much computer time.)

**Grain-scale physics of fault zones.** Fault zones should self-adjust so that some ductile creep occurs. The physics are intuitively simple. Fracturing can only decrease grain size. Grains and amorphous material smaller than 10 nm in diameter are produced efficiently within laboratory fault zones (Yund et al., 1990). However, such very small grains have significant surface free energy and thus are more soluble than large grains. The small grains thus dissolve and reprecipitate as large grains—a process called Ostwald ripening. An equilibrium is reached when small grains are removed as fast as they are created by fracture. Pressure solution creep is then expected because molecular transport between grains is kinetically efficient.

A dynamic steady state with an equilibrium grain size distribution is implied by the simple case of a fault zone with given width and given shear traction. The viscosity of the fault zone is obtained from a balance between the energy associated with new grain surfaces created by faults and the free energy released as grains grow by Ostwald ripening. For example, the viscosity for an equilibrium grain size distribution where grain-boundary diffusion is rate limiting for both Ostwald ripening and pressure solution is dimensionally

$$\eta = \left[ \frac{12W}{\beta_F \tau_F \nu_F} \right]^{\frac{3}{5}} \left[ \frac{\sigma RT}{\Xi V_m} \right]^{\frac{2}{5}}$$

(3)
where \( W \) is fault zone width, \( \beta_F \) is the fraction of elastic strain release that goes into creating new grain surfaces, \( \tau_F \) is the shear traction on the fault, \( v_F \) is the long term velocity of frictional movement on the fault, \( R \) is the gas constant, \( T \) is absolute temperature, \( V_m \) is molecular volume, and \( \sigma \) is the surface free energy of grain-grain surfaces. The creep rate in fault zones is likely to be accommodated by pressure solution controlled by diffusion along hard load-bearing grain-grain contacts. The effective diffusion coefficient \( \Xi \), which is related to the molecular diffusivity of the grain boundary fluid times effective thickness of the grain boundary channel, is the only parameter in the expression whose order of magnitude is well constrained by either field or laboratory data. The coefficient \( \Xi \) can be constrained by creep experiments because the theoretical expression for the viscosity is

\[
\eta = \frac{r^3 RT}{\Xi V_m}
\]

where \( r \) is grain radius (Raj, 1982). Currently available data indicates that the viscosity of real fault zones may be within the range implied by our macroscopic compaction models.

References


Reports

None.
Figure 1: The evolution of fluid pressure, shear traction, and least principal stress are shown as functions of time for several earthquake cycles after a dynamic steady state has been reached (above). Earthquakes result in a drop in all three quantities. Hydrofracture does not occur because fluid pressure is always below the least principal stress. High-aspect-ratio crack and equidimensional pore porosity are shown below. Most of the compaction involves cracks. The model is computed using parameters applicable to a depth of 4.7 km.
Figure 2: The evolution of fluid pressure, shear traction, and least compressive principal stress are shown as a functions of time for several earthquake cycles (above). Earthquakes result in a drop in the first two quantities. The least compressive stress remains nearly constant. Hydrofracture does not occur because fluid pressure is always below the least principal stress. Total porosity, all equidimensional pores, is shown below. There are no cracks in this model. The model is computed using parameters applicable to a depth of 14 km.
Figure 3: The 1-D geometry of two parallel fault splays is shown schematically in top view. The fluid pressure varies within each splay, while the splays share a common shear traction.
Figure 4: The shear traction before failure at earthquakes (denoted by dots) is shown as a function of time for model 2S-3 (above) and model 2S-4 (below) which differ by having different ratios of viscosities between the two fault splays. Failures on the less viscous (weaker) splay are indicated by W and failures on the stronger splay by S. Model 2S-3 is essentially periodic over 6 events, while model 2S-4 is apparently chaotic.
Investigations—The Yellowstone seismograph network (YSN) is operated by the University of Utah through a USGS cooperative agreement and is focused on the most volcanically and seismically active area of the U. S. Cordillera, encompassing the 10,000 km², Yellowstone Plateau and its 45 km by 70 km, 0.6 Ma caldera. The USGS Volcano Hazards and Earthquake Hazards Reduction Program jointly fund this cooperative project with ancillary support from the National Park Service. The Yellowstone Seismic Network (YSN) operates primarily on land under the jurisdiction of the National Park Service and is a joint USGS-University of Utah-NPS cooperative project with support for aspects of the fieldwork in Yellowstone from the NPS. This report covers the second year of a planned 5 yr. upgrade and expansion of the YSN to provide, for the first time, three-component coverage of the caldera to better monitor S wave propagation.

This project provides real-time earthquake surveillance by a newly upgraded and expanded 18-station, single- and three-component, short period seismic network telemetered via four FAA microwave links (via the Sawtelle Peak FAA site 20 km west of Yellowstone and at no cost to the project) to Salt City, Utah, and digitally recorded at the University of Utah. The cooperative agreement provides a service to the U. S. Geol. Survey and is not a direct contract for scientific research, although the data are routinely distributed and used for diverse volcanic, earthquake and ancillary investigations by a federal, state and University users. The cooperative agreement supports the network operations (maintenance, recording and routine data analysis) of the Yellowstone seismograph network with data telemetered to Salt Lake City, Utah.

The University of Utah produces and distributes an annual catalog of earthquake data including map(s) of epicenters, a summary of earthquake information, status of network operations, station maps, a catalog of felt reports of earthquakes (compiled by Rick Hutchinson, NPS), and a summary of earthquake activity for the catalog year. In the event of unusual seismic activity, additional reports summarizing the seismicity with scenarios of possible future activity and statements of precautions that might be taken by government managers. Our primary contacts for such information is our scientific liaison officer, Dr. Dan Dzurisin, USGS Johnson Cascade Volcano Observatory, and the Yellowstone National Park, Superintendent, Research Manager and Public Affairs officers. The Bureau of Reclamation kindly provides data from the Jackson Lake seismic network for better earthquake locations in the southern part of the YSN. For unusual seismicity outside of the park, we also notify local and state officials as well as the U. S. Forest Service and Bureau of Reclamation officials.

Note that because of the remote nature of most of the Yellowstone stations, expensive helicopter, boat, and horseback support is required. Also because of the very difficult operating conditions with several meters of snow, temperatures as low as -60°F, and inaccessibility 6 to 8 months per year the network requires special care with highly reliable equipment and telemetry links built to withstand the rigorous conditions.
Yellowstone Seismotectonics--More than 15,850 earthquakes of $0 \leq M_g \leq 6$ have been located by the Yellowstone network from 1973-1981 and 1983-1993\(^1\). Annual rates of occurrence average ~700 locatable events per year. However, in several cases, intense swarms have produced thousands of correlatable events per month.

The frequency of occurrence of earthquakes changes markedly from more typical, main shock-aftershock tectonic sources outside the caldera in the Hebgen Lake and Yellowstone Lake regions to smaller events characterized by shallow foci and extensive swarms within the caldera suggestive of magmatic sources. In addition there are in several examples of strong correlations between swarms and major changes in the hydrothermal features, suggesting a direct link between the stress release and the source of the hot fluids.

Focal depths of earthquakes within the Yellowstone caldera show sharp variations across the caldera. Maximum foci outside the caldera are generally less than 18 km, but within the caldera, foci seldom exceed 5 km. This pattern of shallowing beneath the caldera suggests the presence of a thin upper-crustal seismogenic brittle layer that is considered capable of sustaining $M < 6$ earthquakes. At depths below ~ km, the crust appears to be in a quasi-plastic ductile state at temperatures in excess of ~400°C, incapable of supporting large stresses owing to high temperatures. The high temperatures are suggested to reflect deeper magma or hot, but solid bodies, related to the Yellowstone volcanism.

Network Upgrade Accomplishments--During the report period, a major commitment was made (see Fig. 1): 1) to upgrade and expand the 15 station Yellowstone network to 18 single- and three-component seismograph stations, 2) add and modify telemetry links with two new microwave links from the FAA Sawtelle Peak site to SLC, and 3) support a student project which operated up to 5 Ref Tek data loggers with Guralp broadband seismometers during winter months for broadband coverage of the Yellowstone caldera. Funds for the student project were from other sources.

Our 1993 efforts were enhanced significantly by the assignment of National Park Service housing at Lake Junction which provided a semi-permanent engineering/work base for our field efforts. Our summer field efforts consisted of a very intense period of hard field work by a three person field team. The project involved extensive network upgrade planning, field reconnaissance, and planning for the major upgrade at the University of Utah computer recording facility. Also the staff of the UUSS was involved with the planning and acquisition of an upgraded recording facility, including a SUN Sparc server for data storage and archiving, four Sparc stations for earthquake data analyses and the installation of a model 7200 Masscomp central recording computer.

Early summer 1993 was devoted to completing environmental assurances of seismograph sites to meet the NPS environmental criteria for seismograph and telemetry installations. We worked closely with the Yellowstone NPS resource management office as well as with the district rangers in careful selection of sights which represented minimal or no environmental problems.

Our primary field accomplishments are as follows (see Fig. 1 for seismic station locations, telemetry links, and radio frequencies):

1. Joseph’s Coat (YCI): Upgrading to three components, moving the site approximate 100 m to a better location for direct telemetry to the Canyon Junction receive site and changing the name and location from the original Hot Springs Basin designation,

\(^1\)Note that the Yellowstone network was not in operation for 18 months in 1982 and 1983.
Summary of October 1, 1992--September, 30, 1993
Yellowstone Seismicity

Number of analyst located earthquakes of $M_C < 2.0$: 53
Number of analyst located earthquakes of $M_C \geq 2.0$: 70
Number of analyst located earthquakes of $M_C \geq 3.0$: 22
Number of analyst located earthquakes of $M_C \geq 4.4$: 2

Total number of located earthquakes: 123

Table of Magnitude 3.5 and Larger Earthquakes In The Yellowstone National Park Region

<table>
<thead>
<tr>
<th>Local Date</th>
<th>Local Time</th>
<th>Mag. $M_C$</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 4, 1992</td>
<td>10:08 am MST</td>
<td>4.0</td>
<td>6 m. NE of Fishing Bridge, Wy.</td>
</tr>
<tr>
<td>Mar 10, 1993</td>
<td>9:49 pm MST</td>
<td>3.7</td>
<td>18 mi ENE of Fishing Bridge, Wy</td>
</tr>
<tr>
<td>Mar 10, 1993</td>
<td>9:56 pm MST</td>
<td>3.7</td>
<td>18 mi ENE of Fishing Bridge, Wy</td>
</tr>
<tr>
<td>Mar 19, 1993</td>
<td>5:30 am MST</td>
<td>4.0</td>
<td>5 mi. SSE of Canyon Jct., Wy.</td>
</tr>
<tr>
<td>Mar 29, 1993</td>
<td>5:09 pm MST</td>
<td>3.7</td>
<td>7 mi SSW of West Yellowstone, Mt.</td>
</tr>
<tr>
<td>May 11, 1993</td>
<td>7:20 am MDT</td>
<td>3.6</td>
<td>18 mi NE of Fishing Bridge, Wy</td>
</tr>
<tr>
<td>Aug 19, 1993</td>
<td>1:43 pm MDT</td>
<td>3.1</td>
<td>10 m NNW of Madison Jct., Wy.</td>
</tr>
</tbody>
</table>

Reports and Publications Reporting or Substantially Using Yellowstone Seismograph Network Data


2. Pelican Cone (YPC): Upgrading, refurbishing the electronics, and moving the seismometer to a better site approximately 30 north of the Pelican Cone fire lookout for more reliable telemetry,

3. YIT (near Lake Junction): Upgrade of solar panel to 30 watts,

4. Lake Butte (YLA): Upgrade of solar panel to 30 watts with new batteries,

5. Mary Lake (YML): Installation of a new three-component station about 200 m west of the old Mary Lake USGS seismograph station with a direct radio telemetry link to Sawtelle Peak receive site,

6. Old Faithful (YFT): Moving and upgrading the original Old Faithful station to a site about 2 km east near the water reservoir tank. The station has been upgraded to three components with a direct RF telemetry link to the new Purple Mountain relay site,

7. Purple Mountain (YPM): Moved the old Madison Junction station to a new site about 2 km north to a remote location at the top of Purple Mountain with the signal directly RF transmitted to Sawtelle Peak. This site is also a receive site for the Norris Jct. and the Old Faithful station,

8. Norris Junction (YNR): Upgrading and moving the old Norris Junction station southeast 2 km to the Mountain Bell telephone repeater site with a direct RF telemetry link to the Purple Mountain relay site,

9. Holmes Hill (YHH): Installation of a new three component seismic station nearer to the most seismicity active area of the Yellowstone system between Grayling Junction and Norris Junction approximately 2 km south of Mount Homes with a direct radio telemetry link to Sawtelle Peak,

10. The acquisition of two additional data channels from the FAA Sawtelle Peak site (SPAX) directly to the Salt Lake City airport FAA facility for a total of 4 lines which are provided at no cost to the project,

11. Installation of a new 30 ft. snow and ice resistant steel antenna tower at the Sawtelle Peak FAA site to bring our installation up to FAA standards for reliable and safe winter operations,

12. Incorporation of the new and modified station signals into a new computer recording system at the University of Utah Seismograph Stations for recording on a Masscomp 7200.

Because of the remote nature of the YSN field work, extensive backpacking, horse packing, and helicopter access were required. Our personnel hiked into to all sites (except Joseph’s Coat Springs) with the support of NPS horse packing and helicopter transport of the heavy and sensitive electronic equipment. We especially thank the NPS and the personnel at the Sawtelle Peak site for their cooperation and work supporting our operation.

Yellowstone Seismicity (October 1, 1992-September, 1993)--Fig. 2 shows the epicenter map for the Yellowstone study area (latitude 44° 07'N to 45° 07'N, and longitude 109° 40'W to 111° 30') for the 123 earthquakes (Mc<4.4) located for the Yellowstone recording area during the reporting period, October 1, 1992-September, 1993.

Figure 1. Telemetry map of the Yellowstone seismograph network. The solid lines represent radio signal telemetry paths, with the radio frequencies indicated for each line. The dashed lines represent telephone relay paths. The triangles show the locations of seismograph stations, with VCO frequencies and station codes listed for each site. The squares with crosses show the locations of telemetry relay points.
Yellowstone National Park Region Seismicity

Figure 2. Epicenter map of earthquakes located in the Yellowstone National Park region from October 1992 to September 1993. The 600,000 year old caldera boundary is from Christiansen (1993).
THE SOUTHERN APPALACHIAN COOPERATIVE SEISMIC NETWORK: VIRGINIA TECH COMPONENT

Agreement No. 1434-92-A-0971

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OBJECTIVES

A major goal of this 1991-1994 cooperative project involving Virginia Tech, Memphis State University, the Tennessee Valley Authority (TVA), and the University of North Carolina at Chapel Hill (UNC) is to provide modern instrumental coverage of seismicity in the southern Appalachians. Stations of the Virginia Tech and Memphis State networks are being upgraded with three-component sensors, high dynamic range electronics, and radio telemetry. Incorporation of the TVA and UNC networks will bring on-line the fully integrated Southern Appalachian Cooperative Seismic Network (SACSN). Calibrated digital waveform data recorded by each SACSN member institution network will be made available in near real-time via the Internet to the other member institutions and the general seismological community. This cooperative regional network is scheduled to be integrated into the U. S. National Seismic Network.

Research objectives for the SACSN are focused on seismic activity in the southern Appalachian region (Figure 1). Research areas include earthquake monitoring (in part to maintain continuity of earthquake catalogs), seismic hazard assessment, studies of the seismotectonics of the region, earthquake source studies, wave propagation at local and regional distances, crustal structure studies, and the temporal/spatial behavior of seismicity. Service objectives of the SACSN include the publication of an annual seismicity bulletin for the southeastern United States; the development and maintenance of regional earthquake catalogs; and informational service to state/local governments, the engineering community, and the general public.

This report summarizes only the Virginia Tech portion of the SACSN project.

NETWORK OPERATIONS

Current Status:

For the past several years, Virginia Tech has operated a calibrated network comprised currently of eleven short-period stations (Figure 2). The telemetry is analog, mostly via phone lines, to the data collection center on the Virginia Tech campus in Blacksburg (near BLA; Figure 2). Each channel is then digitized by a 12-bit sampler at a rate of 100 sps. The effective dynamic range of the entire system is approximately 40 dB. The Giles County subnetwork consists of six stations (3 three-component stations), and the central Virginia subnetwork has five stations (1 three-component station).
Figure 1. (Upper) Epicenters for 1992 earthquakes reported in Southeastern U. S. Seismic Network Bulletin 27. (Bottom) Epicenters for earthquakes during the period July 1977 through December 1992.
Figure 2. Current configuration of the Virginia Tech seismic network (solid triangles are three-component stations). The Giles County subnetwork is in western Virginia and southern West Virginia. The central Virginia subnetwork is the more diffuse cluster of stations in the central portion of Virginia. The upgraded network configuration will be approximately the same as shown here with all stations having three components. BLA and CVL are near the data collection nodes for the upgraded network.

An anonymous ftp account has been established for providing access to waveform data recorded by Virginia Tech. Special waveform data sets recorded by the network and/or the high dynamic range six-component GSE seismograph system at BLA, can be accessed. In addition to the special waveform data sets, triggered event files from the digitizing system are put on the anonymous ftp account within 20 minutes of the trigger time. A description of how to access waveform files, calibration files, etc., is in *Southeastern U. S. Seismicity Bulletin 27* (July 1993).

Network Upgrade:

The upgraded network will continue to have 11 stations with essentially the same configuration. All stations will have three-component sensors, use 24-bit field digitizers (REF TEK model 72-06), and use radio telemetry to transmit digital data back to one of two collection nodes. Data from the Giles County subnetwork will be collected in Blacksburg, and data from the central Virginia subnetwork will be
collected at the Virginia Division of Mineral Resources in Charlottesville (near CVL; Figure 2). The Charlottesville and Blacksburg data collection nodes will be connected using the Internet. The Giles County subnetwork upgrade will be completed by the end of calendar year 1993, and the central Virginia subnetwork upgrade is scheduled to be completed by the end of 1994.

A USNSN station is being installed at BLA. The 300' borehole was completed in October 1993. Installation should be completed by early 1994.

RESEARCH

Virginia Probabilistic Seismic Hazard Assessment:

The objective of the Virginia seismic hazard study is to provide a consistent representation of the mean hazard, organized along jurisdictional boundaries, useful to regulators and planners in state and local governments as well as the engineering community. The result is an evaluation of the seismic hazard at over 150 locations within Virginia and adjacent states, including at least one population center in each Virginia county. The chief products are maps and tables depicting the 1.0 Hz and 3.3 Hz pseudo-relative acceleration elastic response (5% damping) with 10% probability of exceedance in 50 years. These maps are analogous to the preliminary spectral response maps in the 1991 edition of the NEHRP recommended provisions for the development of seismic regulations for new buildings (Building Seismic Safety Council, 1991). Additional information is derived for the construction of simulated ground motion time series compatible with the chosen hazard level at various localities within Virginia. Hazard estimates will be compared with a county-by-county compilation of intensity effects reported from past earthquakes.

The method used to quantify the seismic hazard is that developed by Cornell (1968). Important assumptions include the validity of a simple Poisson model for earthquake occurrence, with a truncated exponential magnitude probability density function. Area earthquake source zones are defined, wherein the probability of seismicity is assumed to be spatially uniform. These source zones are delineated on the basis of the historical earthquake record, recent geological and geophysical investigations, and the results of 15 years of seismic network monitoring (Figure 3). Selection of model parameters defining the mean rate of seismicity as well as the form of the magnitude density function for the various source zones is based on an analysis of the combined catalogs of historical and instrumentally recorded earthquakes (Bollinger et al., 1989). Maximum moment magnitudes are fixed at 7.5 for all source zones within and adjacent to Virginia. Ground motion prediction is performed using the Boore and Joyner (1991) models for deep soil sites. Random error associated with the prediction models is incorporated as a log-normal deviate with constant standard deviation. Figure 4 shows maps for 1.0 Hz and 3.3 Hz PSA at deep soil sites.

The hazard model is used to identify the magnitude-distance combination(s) compatible with the mapped oscillator response values and their associated probabilities of exceedance. This is accomplished by evaluating the magnitude-distance probability density function for the 1.0 Hz and 3.3 Hz oscillator responses at the 475 year return period hazard level. The "most likely" events (in terms of magnitude and distance) contributing to seismic hazard are defined by the maxima of the density function (Figure 5). This information can be used to select, on a
consistent basis, recorded earthquake ground motion time series for dynamic analysis or to generate synthetic time series having a well defined probability of exceedance. Figure 5 also illustrates this additional element of the analysis, for a deep soil site in Richmond, Virginia.

Preliminary results from this work have been presented at the FEMA Annual Earthquake Program Information Exchange Workshop in Seattle, Washington (June 1993) and the Eastern Section of the Seismological Society of America meeting in Weston, Massachusetts (October 1993).

Figure 3. Source zones and seismicity that dominate seismic hazard in Virginia.
Figure 4. Probabilistic seismic hazard maps for Virginia. The upper plot shows the 1.0 Hz pseudo-relative acceleration response (5% damping) for deep soil conditions, expressed as a percentage of gravity, with 10% probability of exceedance in 50 years. The lower plot shows similar results for 3.3 Hz pseudo-relative acceleration response.
Figure 5. (Upper) Magnitude-distance probability density for 10% probability of exceedance in 50 years at Richmond, Virginia: Left: 1.0 Hz PSRV, 4.9 cm/sec from a $M_N = 6.2$ earthquake at a distance of 60 km; Right: 3.3 Hz PSRV, 4.1 cm/sec from a $M_N = 5.4$ earthquake at 20 km. (Bottom Left) Smoothed response spectra for a $M_N = 6.2$ earthquake at a distance of 60 km (solid) and a $M_N = 5.4$ earthquake at a distance of 20 km (dashed). (Bottom Right) Acceleration time series (cm/sec$^2$) for a $M_N = 6.2$ earthquake at a distance of 60 km (upper) and a $M_N = 5.4$ earthquake at a distance of 20 km (lower).

The Eastern Tennessee Seismic Zone:

Virginia Tech and UNC have been awarded a grant by the U. S. Nuclear Regulatory Commission to study the seismicity of eastern Tennessee (Figure 1). An objective of this study is the compilation and organization of over 7000 P and S wave arrival times from over 300 earthquakes which will then be used in a joint inversion for hypocenter location and velocity structure. Additionally, focal mechanism solutions will be determined for most well recorded earthquakes in the area. The velocity structure within the seismogenic region, earthquake locations, and orientation of fault planes, as well as other existing geophysical elements (e.g., potential field data, seismic lines, etc.) will be critically examined in an effort to develop plausible tectonic models for the seismic zone.
The Southeastern U. S. Seismicity Bulletin 27 for calendar year 1992 was distributed this past July to over 230 institutions and individuals. There were 95 tectonic (i.e., non-reservoir related) earthquakes reported in the Bulletin for 1992 (Figure 1). The current southeastern U. S. catalog now includes 1270 tectonic earthquakes and 681 reservoir-related events for the period from July 1977 through December 1992 (Figure 1). The largest 1992 shock was on 21 August in Summerville, South Carolina (mLg = 4.1, I0 = VI). In addition to reporting the usual hypocentral parameters, magnitudes, etc. for the report period, the Bulletin included a report of the effects of the 21 August, South Carolina, earthquake and a description of how to access digital waveform data at Virginia Tech via anonymous ftp over the Internet.

Virginia Tech is also in the process of providing the Virginia Department of Environmental Quality and various engineering firms information necessary to evaluate siting permits.

RELATED PUBLICATIONS AND REPORTS


REFERENCES CITED

recurrence relations for the southeastern United States and its subdivisions, *J.

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Building Seismic Safety Council, (1991), NEHRP recommended provisions for the
development of seismic regulations for new buildings, *in* Federal Emergency
Management Agency Earthquake Hazards Reduction Series 16, no. 222, Part 1,
provisions, *and* Earthquake Hazards Reduction Series 65, no. 223, Part 2,
Commentary.

1583-1606.
Investigations

This project does theoretical mechanical analysis of earthquake faults and tectonic plates. In FY93 the project studied two problems: faulting and seismicity in the New Madrid area, and faulting at Parkfield, California, as related to precursory phenomena.

New Madrid Seismic Zone

The goals here are to construct a mechanical model that explains why the New Madrid seismicity zone exists, what determines the length and maximum possible earthquake magnitude for the zone, and what the repeat time of great earthquakes could be. The mechanical reasons for segmentation and variable diffuseness of microseismicity are also being studied. This work is with T. Hildenbrand and V. Langenheim of the USGS.

Parkfield Precursors

A previously published model for earthquake instability at Parkfield has been modified to use the fault constitutive law developed by Dieterich, Kosloff, Liu, Rvina, Tse, and Rice. The models simulate fault stress and slip over repeated complete earthquake cycles and predict that accelerated precursory faulting occurs before the mainshock instability. The anomalous fault slip causes ground deformation anomalies which in some cases appear to be large enough to detect in field data before the mainshock. This work is with T. Tullis of Brown University.

The fault slip history predicted by the model is used to calculate the piezomagnetic field at the ground surface. The calculation is made possible by a new analytic solution by Y. Sasai for the piezomagnetic field due to slip on a buried rectangular fault. This work is with P. Banks and S.-W. Liu of Case Western Reserve University and Y. Sasai of the University of Tokyo.

The motivation for full-cycle model simulations is that predicted preseismic anomalies, if they can be detected in field measurements, could be used to estimate the time of the next Parkfield mainshock.
Results

New Madrid Seismic Zone

This work, just begun, proceeds from two main assumptions. First, seismic and aseismic faults in the mid-continent region are driven mainly by a northeast-southwest directed far-field compressional plate stress. Second, locations of faults are determined mainly by stress concentrations associated with spacial changes of crustal elastic properties and strength. At the southwest end of the seismic zone the broad distribution of seismicity within a 30 km wide pluton may be partly due to relatively high shear modulus of the pluton. The pluton acts as a relatively stiff inclusion in the stress field of a screw dislocation near its lower edge; the screw dislocation represents the top of strike slip faulting at depth. The overall New Madrid seismic zone appears to be caused by the interaction of the low rigidity Missouri batholith and the Reelfoot Rift.

Parkfield Precursors

Because the model simulates all stages of repeated earthquake cycles, one could in principle estimate values of model parameters (mainly fault properties) using field data for a past stage and then predict a future stage. At Parkfield we find that creep and trilateration data do not constrain model parameters well enough to predict the mainshock time with any useful precision. But if the next mainshock is assumed to have recurrence time and moment within the range of past values, predicted strain anomalies, as measured by extant borehole dilatometers and strainmeters, would be large enough to detect at least several weeks before the mainshock. Creep and trilateration precursors are too small to detect in this model, but were large enough to detect in a previous model based on a strain hardening and softening fault law. When fault properties with the new fault law are assigned from laboratory measurements anomalies are somewhat smaller than when field data are used to constrain parameters.

The maximum piezomagnetic total field change calculated for the time between mainshocks is about 1 nT, located near the Middle Mt. position. Coseismic slip cancels most of the interseismic anomaly. Preseismic anomalies during the final few days before the model mainshock are also greatest near Middle Mt., but have magnitude of about 0.01 nT, and thus are too small to detect with current instruments.

Manuscripts on the fault model and the piezomagnetic calculation are nearly ready for submission to a journal.

Reports


Hildenbrand, T. G., V. E. Langenheim, and W. D. Stuart, Fault characteristics inferred from aeromagnetic data: application to the New Madrid seismic zone (abstr.), *Eos Trans. AGU*, 74, 223, 1993.


Earthquake Hazard Research in the Greater Los Angeles Basin and Its Offshore Area

Agreement # 14-08-0001-A0620

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INVESTIGATION UNDERTAKEN: The Los Angeles metropolitan and offshore areas surround urban centers of high population density that coexist with high earthquake hazards. A special purpose seismic network has been established and has been in operation for the past 20 years. Against the noisy background of urban centers, this network achieves its objective through deployment of both downhole and surface seismometers, through a diligent field instrument maintenance and calibration program, and through up-to-date data processing. Presently, the Los Angeles basin seismic network recording center at U.S.C. digitizes 70 channels of telemetered data from on land (surface and downhole) and offshore stations. This network is an important part of the research activity coordinated by the Southern California Earthquake Center (SCEC).

RESULTS OBTAINED: The principal tasks accomplished are:

A. Operate the Los Angeles Basin Seismic Network (LABNET), a high-performance special-purpose network and obtain on-scale seismic data necessary for earthquake hazard reduction studies in the greater Los Angeles basin and its offshore area. Perform diligent maintenance of all downhole seismic stations and OTS telemetry equipment that insures the high data quality.

B. Perform data processing to prepare regular bulletins and distribute bulletins to the scientific community and public agencies.

C. Carry out data exchange and communication between the LABNET and the USGS/CIT Southern California Seismic Network. Currently, 16 channels of seismic data are exchanged in real-time between these two networks. This exchange augments the seismic coverage for both networks at only nominal phone line cost.

D. Bring any significant changes in the pattern of local seismicity to the attention of the Southern California Earthquake Center and the U.S. Geological Survey.

E. Update the Los Angeles basin network database with data gathered by the network for research on seismotectonics, earthquake hazards, and earthquake prediction in the Los Angeles area.
F. Increase the reliability and the data quality of the remote field stations. Most stations may be equipped with three-component seismometers as well as the OTS gain-raining telemetry circuit.

Besides the above accomplishments related to the network operation, we have concentrated on seismotectonic analysis based on data recorded in the Los Angeles basin during the past 20 years. Comprehensive studies have been completed of:

(1) S-wave splitting analysis and its implications on crustal crack density and regional stress distribution;

(2) detailed analysis of 3-D distribution of earthquakes along the Newport-Inglewood fault;

(3) a detailed inversion analysis on the propagating fault rupture of the 1987 Whittier Narrows earthquake;

(4) site response and near-surface Q-values using weak motion data, strong motion data and data from a downhole array; and

(5) seismic response of a 2-D and 3-D sedimentary basin, and the propagation of short-period surface waves in 3-D basins by Gaussian beam synthesis.

NEW RESEARCH FINDINGS:

MAPPING THE STRESS FIELD

We have systematically calibrated the LABNET followed by a thorough examination on 3-component seismograms recorded since 1988 for evidence of shear-wave splitting for crustal rock at depth beneath the Los Angeles basin. We observed 20-120 ms traveltime difference between the two split shear waves for earthquakes occurring in the crystalline basement at depths of 6-18 km beneath the Los Angeles basin. We interpret the observed shear-wave splitting to be caused by stress-induced crustal anisotropy. We suggest that the seismic anisotropy is mainly the result of microcracks aligned in the direction of maximum principal stress at the crustal depth.

Based on analyses of shear-wave splitting data in the Los Angeles basin, we did not find significant temporal variation of shear-wave splitting before and after the M5.5 Upland earthquake (on Feb. 28, 1990), M5.8 Sierra Madre earthquake (on June 28, 1991), and Joshua-Landers-Big Bear earthquake sequence (on April 22 and June 28, 1992, respectively). These three big earthquakes occurred with epicenters about 60 km, 40 km and 120 km away, respectively, from the network center.

We shall continue to search for evidence of shear-wave splitting in the Los Angeles basin area using LABNET data and the data recorded by portable instruments set up in the basin area. Based on analysis of shear-wave splitting data, we shall produce two maps: one map shows the distribution of directions of principal stresses at depth in the Los Angeles basin, inferred by polarizations of shear waves, and the other map shows the distribution of stress level or the degree of crustal rock fracturing in the Los Angeles basin, inferred by time difference between the two split shear waves.
SHORT-PERIOD SURFACE WAVES IN SOUTHERN CALIFORNIA 3-D BASINS

The occurrence of the M = 7.5 Landers earthquake offers an unusual opportunity for the study of relatively long wavelength energy propagation in southern California basins, where large man-made structures are exposed to potentially damaging shaking as a consequence of focusing effect due to crustal heterogeneities. We have approached this hazard problem by constructing an initial 3-D model of southern California based on available crustal velocity models, from which phase and group velocity maps are generated. Dynamic ray tracing is applied to the generation and propagation of surface waves due to the Landers twin event (a M = 7.5 and a M = 6.5 events 10 sec apart). The bending of rays due to local heterogeneities displays remarkable focusing and defocusing effects, which directly affect the local strong shaking amplitudes. Observations in the Los Angeles basin (Inglewood station) and over southern California are simulated by applying the surface-wave Gaussian beam method that is particularly useful in calculating waves in a 3-D basins such as the Los Angeles. A forward modeling procedure is applied that successfully perturbed the southern California crustal structure in order to obtain an excellent fit to the observations. The result also shows that a twin source is required that is in excellent agreement with near source observations. Implication of this type of study is the development of the ability of a quantitative evaluation of shaking hazard in the Los Angeles basin if and when the so-called Big One does come.

REAL-TIME SEISMOLOGY USING ARTIFICIAL NEURAL NETWORK

This application is particularly appropriate for the LABNET in the Los Angeles basin where signal-to-noise ratio is low and type of ambient noises is numerous. We have been, as part of our effort for improvement in network operation, experimenting an application of neural network-based pattern classification system to the seismic event detection. Two types of AAN are designed for realtime earthquake monitoring in the Los Angeles basin: Type A uses a recursive STA/LTA ratio as input feature, and Type B uses moving window spectrogram as input feature. Some of our sample results are given here. Further development along this line should significantly improve the automation of the LABNET operation.

REPORTS PUBLISHED

a. Refereed Journals:


b. Abstracts:


THE NEW ENGLAND SEISMIC NETWORK  
(Operated Collaboratively by M.I.T. and Boston College)

Contract no. 1434-92-A-0974
Program Element 1

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NETWORK OPERATIONS

The Earth Resources Lab at M.I.T. maintains and operates the M.I.T. Seismic Network as part of the New England Seismic Network under a collaborative arrangement with Weston Observatory of Boston College. The Earth Resources Lab and Weston Observatory are continuing to upgrade and reconfigure the New England Seismic Network (NESN). The NESN is undergoing a significant transition in 1993 that will continue into 1994. As of September 30, 1993 phasing out of funding for seismic data telemetry was completed by the Nuclear Regulatory Commission. At this writing, funds allocated by the Federal Emergency Management Agency to purchase hardware for the new seismic stations of the New England Seismic Network have been received by Boston College. Procurement of the acquisition hardware and software from Nanometrics Corporation is now underway, and delivery of the equipment for fifteen new stations is expected within the next two months. Siting of these stations will be carried out jointly by the Earth Resources Lab and the Weston Observatory, and is scheduled to begin immediately following the first deliveries. It is anticipated that all fifteen stations will be operational by the end of 1994. Currently, three experimental stations are being tested and modified before being deployed for routine monitoring of earthquakes as part of the new generation of seismic stations of the NESN. Three-component wideband seismic systems are replacing the present short-period, mostly vertical component only stations. The new stations detect and digitally record the data at the field site, and are accessed by a dial-up procedure to transfer the data to the central facility (i.e., Earth Resources Lab or Weston Observatory). Using the dial-up method, telephone lines will only be used when stations are being checked for recording status or accessed to download the data, thus greatly reducing the cost of telemetry.

To maintain a minimal regional earthquake monitoring capability while the new stations are being installed, the Earth Resources Lab of M.I.T. is presently operating five stations (Figure 1) in eastern Massachusetts and central and southern New Hampshire, using both M.I.T. and USGS funding. In addition, Weston Observatory of Boston College continues to operate Station WES in Weston, Massachusetts. The Massachusetts and New Hampshire areas covered by the remaining six stations have the highest seismic risk in New England because of a high rate of seismicity and a greater population density than other regions of New England. In addition, these six NESN stations significantly enhance the earthquake detection capability of the four stations of the National Seismic Network (NSN) now operating in New England.

An FTP anonymous account is available to provide on-line access to the most recent one year of digital waveforms and phase data files for local earthquakes. Older data can also be acquired through the FTP account by special request. Details on accessing this account can
be obtained by contacting Charles Doll at 617-253-7863 or doll@erl.mit.edu. The waveforms are in SAC binary format.

SEISMICITY

The M.I.T. Seismic Network consists of digitally recorded short-period stations located in central and southern New Hampshire and eastern Massachusetts. Data from these stations are routinely analyzed to provide hypocentral, origin time and magnitude information for local earthquakes. Quarterly bulletins, reporting earthquakes in and adjacent to the M.I.T. Seismic Network, are published and available for the period October 1979 - March 1993.

Figure 2 shows the epicentral locations of local earthquakes within or adjacent to the M.I.T. Seismic Network for the period October 11, 1992 - October 10, 1993. Eleven earthquakes, with a magnitude range Mc 1.8 - 2.9, occurred during this period. Five occurred in central New Hampshire, the area historically having the highest seismicity rate within the M.I.T. Seismic Network including two potentially damaging earthquakes in December 1940 (ML=5.3 and 5.4; Ebel, Somerville and McIver, 1986) and one in January 1982 (M=4.7).

CURRENT RESEARCH

Two major research projects, begun in 1992, have been continued and expanded in 1993. First, a waveform correlation / relative location technique is being applied to seismicity in the central New Hampshire and the Charlevoix, Quebec seismic zones (Toksoz et al., 1993) to establish high accuracy hypocentral locations for seismicity in those regions. Significantly reduced scatter in the spatial distribution of the seismicity may define the orientation and dimensions of specific geologic structures. Second, an empirical Green's function (EGF) method (e.g., Li and Thurber, 1988) is being applied to event pairs (Li, Y. et al., 1993), earthquakes with similar hypocenters and focal mechanisms identified by the relative location technique, to estimate a relative source time function (STF) for the larger event. The STF is being used to derive important fault parameters such as fault length, stress drop and rupture directivity.

In another study, the EGF technique has been applied to retrieve the relative STF of the October 1992 Colombia earthquake (Li and Toksoz, 1993), Ms=7.3. An Ms=6.7 foreshock was treated as the EGF. The relative STFs of the larger event were recovered from Love waves recorded by 17 IRIS Global Seismic Network (GSN) stations, and were stacked to yield an average STF (Figure 3, top). The stack trace and the individual GSN station seismograms both show two main pulses, representing the main shock and an aftershock approximately 100 s later. Also, a double event, consisting of a smaller pulse followed by a larger one 12 s later, is observed on both the stack trace and some of the GSN station records. These STF features are verified by seismograms recorded by 5 short-period M.I.T. Seismic Network stations. The vertical component velocity records of the Ms=7.3 and 6.7 earthquakes recorded by these 5 M.I.T. stations were aligned to initial P, stacked, and then squared to calculate the stack "power" traces (Figure 3, bottom) for the two events. The times of the two subevents of the Ms=7.3 main shock (about 12 s apart) and the aftershock 100 s later are corroborated by high amplitude features on the stack "power" trace for this event. However, the stack "power" trace of the Ms=6.7 foreshock reveals only a single pulse indicating a simpler event.
A third research investigation (Cicerone, 1992; Cicerone et al., 1993) using data recorded by the New England Seismic Network is now underway to calculate the relative contributions of scattering ($Q_s^{-1}$) and intrinsic attenuation ($Q_l^{-1}$) as a function of frequency and distance in the New England crust. The energy-flux model of seismic coda, developed by Frankel and Wennerberg (1987), is being used to derive estimates of scattering and intrinsic attenuation. The model predicts the amplitude of the S coda wave over time as a function of frequency, $Q_s^{-1}$ and $Q_l^{-1}$. The results of this study will provide important information for the accurate prediction of ground motions as a function of distance and frequency for earthquakes in New England.

Preliminary measurements of $Q_s^{-1}$ and $Q_l^{-1}$ obtained from seismograms (Figure 4) from a single event indicate that both scattering and intrinsic attenuation are important mechanisms of energy dissipation. The significant exception to this occurs at short distances, where the results at a station (WFM) only about 6 km away from the epicenter seem to indicate that scattering may be more important near the source (Figure 5). The values of $Q_s^{-1}$ and $Q_l^{-1}$ obey a power law as a function of frequency and typically range from 0.01 at low frequencies to 0.001 at higher frequencies (i.e., about 25 Hz).

Further analysis of 49 events recorded on the M.I.T. New England Seismic Network from 1989 to 1993 (Figure 6) show a strong correlation of $Q_s^{-1}$ with distance, with the highest scattering at short distances and a strong decrease in scattering with increasing distance (Figure 7). However, a similar analysis of $Q_l^{-1}$ with distance shows no apparent trend, and instead indicates a large amount of variation in the results (Figure 8). These preliminary values are consistent with other attenuation studies conducted in New England (e.g., Pulli, 1984; Toksöz et al., 1990).

Further work is planned to determine if $Q_l^{-1}$ exhibits either depth dependence or is localized to particular geologic regions in New England. Moreover, the study will be extended to measure $Q_s^{-1}$ and $Q_l^{-1}$ for a large number of earthquakes over a wide azimuthal distribution of ray paths (including Weston Observatory station data). This will yield a 3-D model of the spatial variation of scattering and intrinsic attenuation in the crust of New England.

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**PUBLICATIONS**

Figure 1: Five M.I.T. stations (triangles) and the Weston Observatory station WES (box) operating after September 30, 1993. These six stations of the present NESN will provide earthquake coverage (along with four USGS NSN stations) while the NESN is reconfigured with 15 new seismic stations in late 1993 and 1994.
Figure 2: Seismicity of New England recorded by the M.I.T. Seismic Network for the period October 11, 1992 - October 10, 1993. The M.I.T. seismic stations are shown as triangles (network configuration up to September 30, 1993).
Figure 3: Relative STFs (top) for the 1992 Colombia earthquake (M=7.3) derived using the EGF technique applied to Love waveforms recorded by 17 GSN stations. The numbers following the station names are source-to-receiver azimuths. The average STF (stack) and the individual station STFs show the main shock and aftershock about 100 s apart, and the two subevents of the main shock about 12 s apart. This source sequence can also be observed on the stack “power” trace (bottom) of the M=7.3 earthquake, generated from short-period seismograms recorded by the M.I.T. Seismic Network.
Figure 4: Seismograms of the January 23, 1990 northeastern Massachusetts earthquake recorded at distances of about 6 km (station WFM), 80 km (station DUX), and 145 km (station WNH). Amplitudes are not corrected for differences in instrument gain among the three stations.
Figure 5: Estimates of $Q_S^{-1}$ (scattering) and $Q_I^{-1}$ (intrinsic attenuation) as a function of frequency at short (WFM), intermediate (DUX), and long (WNH) distances. These values were obtained by inverting narrow-bandpass filtered waveforms obtained from the seismograms in Figure 4 using a modified Levenberg-Marquardt algorithm.
Figure 6: Map showing the stations of the M.I.T. New England Seismic Network (triangles) and epicentral locations of the 49 events (asterisks) used in this study from the period 1989-1993.
Figure 7: Plot of $Q_s^{-1}$ (scattering) vs. distance for the 49 events shown in Figure 6. Note the strong dependence of scattering with distance and the relatively high values of scattering at short distances, indicating that scattering may be predominantly a near-field mechanism.
Figure 8: Plot of $Q_i^{-1}$ (intrinsic attenuation) vs. distance for the 49 events shown in Figure 6. Note the large amount of variation in the data.
EXPERIMENTS ON ROCK FRICTION CONSTITUTIVE LAWS APPLIED TO EARTHQUAKE INSTABILITY ANALYSIS

USGS Contract 14-08-0001-G-1364 - 2278

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INVESTIGATIONS:
1. Fluid chemistry effects on detailed frictional behavior.
2. Frictional behavior of all three polymorphs of serpentine.
3. Determination of low velocity frictional parameters from relaxation tests.
4. Effect of gouge on friction evolution effect.
5. Evolution effect- time or slip dependent?

RESULTS:
1. Surfaces in stationary contact increase in strength with time; this is commonly referred to as the evolution effect. It is the most important aspect of rock friction to understand, because it is responsible for the restrengthening of surfaces between slip episodes and for a tendency for frictional resistance to be lower at higher sliding velocities.

The experiments of Dieterich and Conrad (1984) that show that the evolution effect is eliminated if the sliding surfaces are dried thoroughly have led us to a hypothesis on the origin of the evolution effect. We believe that the evolution effect may be caused by the time-dependent removal of contaminant, most likely adsorbed water, from between contacting surfaces resulting in a stronger bond. If this is true, altering the chemical environment of a sliding surface should alter the frictional behavior in predictable ways. A solution containing electrolytes should make bonding between the surfaces even more difficult than in a neutral pH pure water solution, because the cations become hydrolyzed and attracted to the negatively charged surface, inhibiting the close approach of the surfaces. The electrolytes represent a greater contamination of the surface than pure water and should lead to a greater evolution effect. We postulated that experiments conducted at a pH of about 2.6, the so-called “point of zero charge” for quartz would exhibit little or no evolution effect. At that pH protons imbedded in the surface cancel the surface charge, reducing the tendency for adsorption of water or hydrolyzed cations. This would in turn eliminate the contaminant layer, allowing direct bonding of the silicate surfaces.

We have recently completed some preliminary experiments to test these predictions. The results are shown in Figure 1 for three ten-fold velocity decreases at an identical displacement in three separate experiments using 1 mm layers of ultra-fine quartz powder. In Figure 1a we show a control experiment which is done in atmospheric humidity like the control experiment of Dieterich and Conrad (1984). This experiment contained no liquid water. It shows the typical evolution effect as the decay back up toward the final steady-state level, following the drop due to the direct effect response to the velocity decrease. An experiment done with a solution of nitric acid at an
Other characteristics of the pH 11 experiment are unusual. First, at the longest hold time in Figure 2a the peak strength upon reloading was considerably below the linear trend. Second, after the longest relaxation times, the steady state level after the reload is much lower than the level before the relaxation is started, as shown in Figure 2b. For all of the other experiments the steady state level is reattained after the holds. Third, the form of the relaxation indicates that a new process becomes important at long times, and therefore at very slow velocities. Figure 2c shows three curves of normalized frictional strength versus the log of relaxation time. The experiment at pH 11 shows a dramatic reduction in slope after about 10,000 seconds. This form of the relaxation curve is similar to that seen by Chester and Higgs (1992) in quartz experiments done under hydrothermal conditions and by Reinen (1993) in room temperature experiments on serpentine. In both of these cases the authors determined that a flow process was occurring at the lowest velocities, pressure initial pH of 2.6 is shown in Figure 1b. As predicted, it shows no evolution effect. Finally in Figure 1c we show the results from an experiment buffered at a pH of 11 using a buffer that includes NaOH and NaCl. This experiment shows an evolution effect similar to the control experiment. Figure 2a shows a much larger evolution effect for the pH 11 experiment as determined from hold tests. It is clear from the figure that the strengthening with time is larger for this experiment than any of the others.

As might be expected with only a few experiments so far, there are complications. The results of the pH 2.6 experiment are not completely unambiguous. Only in the first two velocity changes did the evolution effect appear to be absent (Figure 1b). Subsequent velocity changes and slide-hold-slide tests (Figure 2a) showed a typical magnitude for the evolution effect. We believe that the supply of H\(^+\) ions in the solution may have been exhausted early in the experiment, shifting the pH toward more neutral values. The pH in this experiment was not buffered at a pH of 2.6. Because nitric acid completely dissociates, as H\(^+\) ions are removed from solution by the quartz surfaces, it depletes the supply causing the pH to increase. An approximate calculation suggests that the number of H\(^+\) ions was about the right order of magnitude to be completely used up by adsorbing onto the surfaces present at the start of the experiment. Thus there would be no reserve supply of H\(^+\) ions for the greatly increased surface area generated by comminution early in the experiment.
solution for the quartz under hydrothermal conditions and probably dislocation glide for the serpentine. In our experiment at pH 11, we presume that pressure solution was responsible, due to the increased solubility of quartz. This is further supported by analysis of the long-time portion of the relaxation shown in Figure 2c (see below, section 3).

The experiment at pH 11 is also not completely unambiguous. The greater evolution effect might be caused by the Na\(^+\) ions independently of the high pH, as explained above. However, the solubility of SiO\(_2\) is 16 times higher at a pH of 11. If pressure solution is involved in the evolution effect, then high pH might enhance the effect by providing a greater flux of dissolved material. We believe that the increased evolution effect is caused by the presence of Na\(^+\) ions because other manifestations of the increased solubility are present only at very low velocity or at long times.

While there are significant ambiguities in interpreting these experiments, the results are very exciting. We have demonstrated that we can make significant changes in the frictional behavior of quartz by changing the chemical environment of the sliding surface. We have shown several different effects including the possible elimination of the evolution effect by a low pH environment, the enhancement of the evolution, probably by introduction of electrolyte solution, and the appearance of a new process at low velocity and elevated pH which may be pressure solution.

2. We have now conducted friction experiments on all three polymorphs of serpentine: antigorite, lizardite and chrysotile, at sliding velocities ranging from 0.003 to 3.2\(\mu\)m/s. These results are summarized in Figure 3. Chrysotile and lizardite both exhibit low frictional strength (chrysotile 0.2-0.25; lizardite 0.15-0.35); antigorite is as strong as other silicates (0.5-0.85).

Field measurements of stress orientations and heat flow suggest that both continental and oceanic transform faults are mechanically weak relative to the surrounding crust, resulting in low shear stresses across the faults. Other researchers have developed models in which high fluid pressure is trapped within the fault zone by differential permeability or clay seals. The low strength of lizardite and chrysotile serpentinite suggests that the presence of either polymorph on a fault would result in stresses less than half that expected from typical crustal rocks. All three polymorphs show a transition from velocity weakening at fast velocities to velocity strengthening at slow velocities.
This should promote stable aseismic slip.

Our experiments were all conducted at room temperature. Modest temperature increases could result in frictional strength of lizardite or chrysotile below 0.1. This could explain low stress on creeping sections of the San Andreas. Low stress on fault sections that slip only seismically might result from various other mechanisms that operate only during dynamic slip. Thus differing explanations for aseismic and seismic areas could explain low stresses without requiring high pore pressure.

At low sliding velocities, the lizardite and chrysotile polymorphs have very different strengths but similar rate dependence. We believe these mechanical observations can be explained by differences in the crystal structure. Lizardite has only weak hydrogen bonds between structural layers, while antigorite has stronger SiO bonds bridging the layers. The hydrogen bonds may control the rate dependence, while the SiO bonds would give antigorite its strength. Chrysotile, on the other hand, has much smaller velocity dependence at low velocity. We observe that the layer of chrysotile powder forms a felted mass of tangled fibers, probably requiring that fibers break to accommodate slip.

3. We have investigated the use of relaxation tests for determination of frictional parameters at very low velocities. Slide-hold-slide tests are common in studies of rock friction for investigating time-dependent frictional strengthening (the evolution effect). In most cases, data from the relaxation (hold) portion of the test is not used. Relaxation tests are attractive because very low sliding velocities can be achieved in relatively short time (we have reached velocities as low as $3 \times 10^{-3}$ $\mu$m s$^{-1}$).

Because of the finite stiffness of any real apparatus, when loading rate is set to zero the stress and slip velocity fall as sample creep relaxes the machine. Thus, the stress decays by Hooke’s law: $d\sigma/dt = -kV$; $k$ is stiffness, $V$ is slip velocity. This can be combined with the constitutive law for frictional slip to determine the form of the stress relaxation. We have applied this to the constitutive law appropriate for serpentine at low velocity (exponential flow law), a power-law flow law, and to the “slowness” version of the rate- and state-variable friction law.

Analysis of the exponential and power laws is relatively straightforward because they lack the history dependence represented by the state variable in the rate- and state-dependent friction laws. Thus, there is a single-valued relationship between velocity and strength. For these forms we can determine constitutive parameters directly by using our high-resolution resolver to measure sample slip velocity. If slip velocity cannot be measured, we can solve for the form of the relaxation of stress with time and fit this to measurements of stress with time. We have determined the velocity dependence of frictional strength $a$ for the exponential flow law ($\mu = \mu_0 + \ln(V/V_0)$) that
describes serpentine at low velocities both by velocity step tests and by relaxation:

<table>
<thead>
<tr>
<th></th>
<th>Velocity steps</th>
<th>High-V relaxation</th>
<th>Low-V relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antigorite, bare</td>
<td>0.0157; 0.0186; 0.0181; 0.0220</td>
<td>(No data)</td>
<td>(No data)</td>
</tr>
<tr>
<td>Antigorite, powder</td>
<td>0.0296</td>
<td>0.0402 (Vi = 0.316)</td>
<td>0.0182 (Vi = 0.0056)</td>
</tr>
<tr>
<td>Lizardite, powder</td>
<td>0.0230</td>
<td>0.0230 (Vi = 1.0)</td>
<td>0.0197</td>
</tr>
</tbody>
</table>

Low-V relaxations refer to relaxations initiated at sufficiently low velocity to be well into the low-velocity flow field for serpentine; High-V relaxations were initiated at velocities in the state-variable field; the results use only data at velocities low enough to be dominated by the low velocity behavior lacking history dependence. Low-V relaxations agree well with velocity steps on bare surfaces; we believe that the lack of agreement with other determinations results from changes in sliding layer texture. The small amount of slip in the Low-V relaxations and the very thin deformation zone in bare surface runs may prevent such changes in these cases, yielding a number representative of the intrinsic material behavior.

Applying the technique of measuring slip velocity and fitting a constitutive law directly to relaxation data, we have fit a power law ($\mu = \mu_0 + (V/V_0)^m$) to the last part of the relaxation on quartz powder at pH 11 (see Figure 3c). This fit gives a value for the exponent $m$ of 0.92, very close to 1.0 which would be expected from pressure solution creep, adding further support to our contention that the behavior observed at long times and low velocities in this experiment are caused by pressure solution.

If history dependence in the form of a state variable is introduced, the strength is no longer a simple function of the instantaneous velocity and the direct method cannot be used. However, in the case of the state variable evolution law we call the slowness law (see below, section 5), an approximation valid at long relaxation times allows a solution for velocity as a function of time of relaxation. This solution allows determination of the ratio of the frictional constitutive parameters $a$ and $b$ if the material is velocity weakening. On a plot of log slip velocity versus log time, at sufficiently long times the slope is equal to $-b/a$ if $b > a$ (velocity weakening). The parameter $b$ can be determined from the rate of time-dependent strengthening during hold tests. The ratio $b/a$ then allows determination of $a$. If $b \leq a$, then the slope is -1 for all values of $a$ and $b$ and constitutive parameters cannot be determined.

4. The velocity dependence of frictional strength of simulated gouges is not the same as that for initially bare surfaces of the same composition. One explanation for this difference is that gouge velocity dependence consists of bare surface velocity dependence (intrinsic velocity dependence) plus an additional contribution due to dilation against normal stress. However, in experiments that we have reported on previously, the contribution from dilation is not large enough to explain the difference. Understanding how velocity dependence itself can depend on sample configuration is important because the presence of gouge in experiments stabilizes sliding.

We have tested the hypothesis that the intrinsic velocity dependence of gouge is the same as for bare surfaces by measuring the time dependent time-dependent strengthening. If both sample configurations are frictional in the Mohr-Coulomb sense, stress analysis shows that each configuration is required to deform on planes of distinctly different orientation. The measured strength and
intrinsic velocity dependence will reflect this geometric difference. We have performed slide-hold-slide tests on granite bare surfaces and on simulated granite gouge and find that the time-dependent strengthening for the simulated gouge is nearly three times smaller than for initially bare surfaces (Figure 4, symbols). We have also performed numerical simulations of slide-hold-slide tests (Figure 4, lines) and find that the difference is completely accounted for by the geometric difference if we assume bare surfaces measure the intrinsic value of $b$ (the evolution effect) and gouge is represented as a cohesionless coulomb plastic material. It should be noted that the line indicating simulations of the gouge results is derived directly from the bare surface results and is not a fit to the gouge data. The results demonstrate that gouge deformation is fully consistent with Coulomb plasticity, and that the intrinsic constitutive parameter $b$ is the same for both bare surfaces and gouge. The results also suggest that there is no time dependence associated with stabilizing effects in gouge. Deformation as a Coulomb material also implies that observed gouge velocity dependence is a function of observed strength because strength depends on the orientation of the deforming planes. Furthermore, the normal stress on deforming planes will be a function of sliding velocity. Determination of individual constitutive parameters in gouge is not possible unless geometrical effects are properly characterized.

5. As originally shown by Dieterich, the frictional behavior of rocks involves two competing effects in response to changes in velocity: the direct and evolution effects. The evolution effect is negative and is associated with a characteristic length in velocity step tests, but was originally attributed by Dieterich to time-dependent strengthening of frictional contacts. Subsequently, Ruina introduced a generalized differential equation ("Slip Law"), now widely used, in which evolution occurs only as a result of slip and explicit time dependence was lost. Sample creep during the hold portion of a slide-hold-slide test causes apparent time-dependent strengthening in simulations using the slip law. A different equation retains the strengthening with time ("Slowness Law") but is otherwise very similar to the slip law.

To test whether the strengthening with time observed in slide-hold-slide tests is a result of time-dependent strengthening or is caused by sample creep during the hold, we performed slide-hold-slide tests at two machine stiffnesses and compared the results to simulations of slide-hold-slide tests using both the slip law and the slowness law. We find that the observed strengthening with time is independent of stiffness. The Slip Law predicts less evolution for high stiffness because the amount of slip is small. This shows conclusively that the unknown process responsible for the evolution effect is intrinsically time dependent, as originally stated by Dieterich. On the other hand, the Slowness Law, which does have explicit time dependence, does not give the nearly symmetrical response for increasing and decreasing velocity steps that is observed experimentally. This is because the time to slide a given distance is greater at the lower velocity.
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Earthquakes As Self-organized Critical Phenomena
Contract # 1434-92-G-2165
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Investigations Undertaken

The objective of the research carried out is to understand whether earthquakes are an example of self-organized criticality. The approach is to develop analog models which are examples of self-organized criticality and which exhibit the important features of distributed seismicity. These models can then be examined for precursory behavior that can be predictive of major analog earthquakes. The results may provide the basis for new approaches to earthquake prediction.

The research is being undertaken in collaboration with Dr. Andrei Gabrielov who is on leave from the Institute for Theoretical Geophysics and Earthquake Prediction in Moscow and is spending the period of this grant at Cornell. Dr. Gabrielov was a leader in the development of the algorithms that successfully predicted the Armenian, Loma Prieta, and Landers earthquakes. One objective of our research is to test these algorithms on the analog SOC systems.

Results Obtained

It has been suggested that distributed seismicity is an example of self-organized criticality. If this is the case, the Earth’s crust in an active tectonic zone is in a near-critical state and faults can interact over large distances. Observed seismicity and earthquake statistics are consequences of the dynamical interactions of seismic faulting over a wide range of scales. We address this problem by considering a two-dimensional array of slider blocks with static/dynamic friction. The two-dimensional systems is treated as a cellular automaton such that only one slider block is allowed to slip at a given time and interacts only with its nearest neighbors through connecting springs. Because of this treatment, the amount of slip for each failed block can be obtained analytically, and the system is deterministic with no stochastic inputs or spatial heterogeneities. In many cases, the slip of one block induces the slip of adjacent blocks. The size of an event is specified by the number of blocks that participate in the event. The number of small events are close to a Poisson process, and gradually deviate towards periodicity for large events. The recurrence time statistics are generally insensitive to parameter variations. Large events may occur at stress levels considerably lower than the failure strength of an individual block, and the stress drops associated with large events are generally small. This may provide an explanation for observed low stress levels in tectonically active areas. This work has now been published [1, 2].
In the standard cellular-automata model for a fault an element of stress is randomly added to a grid of boxes until a box has four elements, these are then redistributed to the adjacent boxes on the grid. This redistribution may result in one or more of these boxes having four or more elements in which case further redistributions are required. On the average added elements are lost from the edges of the grid. We have modified this model so that the boxes have a scale-invariant distribution of sizes. When a redistribution from a box occurs it is equivalent to a characteristic earthquake on the fault. A redistribution from a small (a foreshock) may trigger an instability in a large box (the main shock). A redistribution from a large box always triggers many instabilities in the smaller boxes (aftershocks). The frequency-size statistics for both main shocks and aftershocks satisfy the Gutenberg-Richter relation with $b = 0.835$ for main shocks and $b = 0.635$ for aftershocks. Model foreshocks occur 28% of the time. This work has been completed and is now in press [3]. A review article on this work is also in press [4].

New lines of research include an application of R/S analysis to earthquake prediction. The rescaled range $R$ represents fluctuations in the level of seismicity relative to the mean $S$. Running values of $R/S$ have been determined for various regions and time windows adjacent to the San Andreas fault. The object was to determine whether variations in $R/S$ systematically preceded major earthquakes. So far no statistically significant precursors have been found.

Reports Published


Heat Flow and Tectonic Studies

9960-10026, -11026, -12026
PROGRAM ELEMENT I

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Investigations:

The investigation of the thermal regime of the Mojave-Sonoran Desert region of California and Arizona has been completed, and the manuscript has received Director’s approval for publication.

Models of the effects of erosion on heat flow in the Cajon Pass drillhole have been revised. A paper discussing the resulting implications for frictional heating along the San Andreas fault is in review for the J. Geophys. Res..

Reconfiguration of laboratory calibration facilities, the transient heat-source conductivity apparatus, and development of a high-temperature thermal conductivity apparatus continued.

A joint study (with Daniel Pribnow of KTB) of thermal conductivities of both core and cuttings from KTB drillholes continued. Work was completed on a joint study of derivation of rock thermal conductivities from geophysical well logs, and the results were published in Geophysical Research Letters.

Downhole experiments in the Long Valley Exploratory well continued.

A study of the relationship between fluid flow in fractured rock and regional stress fields has been initiated. The study utilizes subsurface thermal data to identify fluid flow in situ. A major goal of the study is the characterization of crustal fluid flow in the vicinity of candidate sites for the San Andreas fault deep drillhole.

The initial phase of a detailed investigation of the deep thermal regime of the northwestern Geysers geothermal field was completed. The results were published in the GRC Transactions.

Temperature measurements were made in oil wells in Railroad Valley, Nevada, and in geothermal exploration wells near Ft. Irwin and Ridgecrest, California. The resulting heat-flow determinations will be presented in open-file reports.

Characterization of the thermal regime of the Parkfield region was completed, and high-precision borehole-temperature monitoring in the area continued.
Results:

Mojave-Sonora. More than 200 values of heat flow are now available from the crystalline terranes of southern California, the Basin and Range Province of Arizona, and Paleozoic sedimentary rocks of the southwestern Colorado Plateau (CP). Heat flow ranges from about 5 mW m$^{-2}$ on the CP near Flagstaff, Arizona, to more than 150 mW m$^{-2}$ in the crystalline rocks bordering the Salton Trough in SE California. The heat-flow pattern within this region is complex and appears to be controlled by regional physiographic and tectonic features. Unlike the adjacent Sierra Nevada Batholith where heat flow is a linear function of near-surface radiogenic heat production, no statistically significant correlation exists between these two quantities in the study area. This absence of correlation is attributable to the complex tectonic history, involving lateral movement of basement terranes, and heat sources and sinks of different strengths, ages, and durations. Contemporary and Neogene tectonism appears to be responsible for the very high heat flow (>100 mW m$^{-2}$) associated with the Salton Trough and its neighboring ranges, the Death Valley fault zone and its southward extension, and zones of shallow (<10 km) Curie isotherms (as inferred from aeromagnetic data) in west-central Arizona. Low (<60 mW m$^{-2}$) heat flow in the Peninsular Ranges and eastern Transverse Ranges of California may be caused by thermal transients related to subduction and compressional tectonics. Relatively low heat flow (67±3.5 mW m$^{-2}$) is also associated with the main trend of metamorphic core complexes in Arizona. This is a surprising observation in view of the fact that the processes related to their deroofing have positive thermal transients, with mantle contributions having time constants of tens of millions of years. The outcropping rocks in the core complexes have a low radioactive heat production (1.1 $\mu$W m$^{-3}$); only about half that for the other crystalline rocks in the region. Some, but not all of the nearly 20 mWm$^{-2}$ deficiency related to the metamorphic core complexes can be related to this observation. The overall average heat flow for the presently quiescent southern Basin and Range province (82±3 mWm$^{-2}$) is not significantly different from that for the northern Great Basin, much of which has been actively extending over the past 10 m.y., and is several hundred meters higher in average elevation than the southern Basin and Range. Consideration of simple models for extension indicates that this is the expected result because of the long time constants governing the decay of thermal transients associated with province-wide extension.

Heat Flow at Cajon Pass, California, Revisited. Recent studies in a 3 ½ km borehole near Cajon Pass showed that the observed high heat flow and its sharp decrease with depth are predictable effects of independently determined erosion history, topography, and radioactivity, leaving little room for the large contribution from frictional heat required by conventional faulting models for the nearby San Andreas fault. We have since discovered an error in our analysis that lowers the predicted surface heat flow from the upper end (~100 mW/m$^2$) to the lower end (~90 mW/m$^2$) of the range of measurement uncertainty at this complex site; it permits, but does not require, a source increment of up to 10 mW/m$^2$ not accounted for in the prediction. Better agreement between the prediction and observations at depth confine the permissible extra heat flow to the upper part of the hole, making it difficult to attribute it to a deep frictional source. In any case, however, such a frictional source would be too small to permit conventional high-strength faulting models, and the basic conclusion of the original study is unchanged. The most likely cause
of the relatively small discrepancy between predicted and observed heat flow (if it exists) is preferential three-dimensional flow into the higher conductivity rock that occupies the upper part of the borehole.

**Thermal conductivity of water-saturated crystalline rocks as a function of temperature.** Scientific studies of the continental crust increasingly include the drilling of deep (~ 5 km) and “superdeep” (~ 10 km) research boreholes. Studies of the Earth’s thermal regime rank among the most important scientific goals of these projects. To characterize adequately the variation of heat flow with depth in these boreholes, it is necessary to take account of the relation between thermal conductivity and temperature. A few systematic studies have been carried out on dry crystalline rocks, the most important of which remains the classic work of Francis Birch and Harry Clark in 1940. We have constructed an algorithm relating thermal conductivity to temperature based on the latter results. This empirical relation applies equally well to other experimentally determined conductivity-temperature values irrespective of mineral composition. To our knowledge, no systematic studies of thermal conductivity as a function of temperature have been done on saturated rocks. Although crystalline rocks generally have little porosity (on the order of 1%, mostly fractures), significant errors in thermal conductivity can occur if the pore space is not maintained in a saturated condition during measurement.

**Collaboration with German deep drilling project (KTB).** As outlined in our FY 1992 proposal, approximately 100 additional samples were collected from the pilot hole core. Disks were prepared in two or three orientations so as to characterize vertical, parallel, and perpendicular (to bedding) thermal conductivities. The initial results for the vertical component of conductivity were encouraging in that the majority of values were within 10% of one another (the combined uncertainties of the two techniques), but there were some disagreements that could not be readily explained. A re-examination of the algorithm used to calculate vertical conductivity from the KTB line-source method and a revised measurement strategy resulted in a much better agreement between the two sets of results. It is worth noting here that, without the cooperative study now under way, the shortcomings of the original algorithm would not have been readily apparent, and the improvements in both measurement strategy and interpretive procedures would most likely not have occurred.

The comparison of calculated anisotropies produced a very poor correlation. Typically, both line-source measurements and conductivity disks oriented parallel and perpendicular to the foliation were separated from each other by a few centimeters. This resulted in substantial uncertainties in anisotropy arising from significant differences in mineral composition between measurement sites. A similar problem was noted in the case of Cajon Pass. Because of the uncertainty introduced by variations in mineralogy, the anisotropy can only be specified in general terms as an average for characteristic rock types.

Well-log measurements of compressional and shear velocity ($V_p$, $V_s$), density, and temperature from the 4 km-deep KTB Vorbohrung (pilot hole) were applied in a phonon conduction model for the thermal conductivity of a crystalline solid. The resulting conductivity estimates were compared with conductivities ($k_{LAB}$) measured on the nearly continuous (91% recovery) core. Studies in other boreholes have shown the log-derived
conductivity \( (k_{\text{LOG}}) \) to be within \( \pm 15\% \) of \( k_{\text{LAB}} \) in predominantly isotropic crystalline rocks. The section penetrated by the KTB pilot hole includes both predominantly isotropic metabasites and highly anisotropic gneisses with foliation dips ranging from subhorizontal to nearly vertical. The predictions of the phonon model were accurate in the metabasites but inaccurate by 6% to 23% in the moderate to steeply dipping gneisses. These discrepancies between \( k_{\text{LOG}} \) and \( k_{\text{LAB}} \) correspond to depths at which laboratory measurements of \( V_s \) under \textit{in situ} conditions deviate from the well log \( V_s \). This suggests that full waveform sonic log determinations of \( V_s \) may not be reliable in dipping, anisotropic rocks. Alternatively, the laboratory \( V_s \) measurements may not be drawn from a representative sample, and the discrepancies may follow from errors in the phonon conduction model. Whatever the reason, the validation of the model in the metabasites confirms the utility of the phonon conduction approach in deriving \textit{in situ} thermal conductivity in boreholes for which even a small part of the penetrated section is composed of isotropic or weakly anisotropic rocks. The results also demonstrate that, if the cause of the discrepancy in anisotropic rocks is identified as following from errors in the well log measurements, the close relationship between thermal and elastic properties may provide a tool for deriving thermal conductivity profiles of the middle and upper crust from seismic studies of \( V_p \) and \( V_s \).

The Relationship Between Regional Stress Fields and Fluid Flow as Indicated by Heat-Flow Measurements in Crystalline Rocks. The fracture permeability of crystalline rock is dependent upon a number of factors, including the orientation and magnitude of \textit{in situ} stresses, the interaction of fluid chemistry with mineralogy, the effects of weathering, and the history of local tectonics. If deviatoric stresses in the upper few kilometers of the crust are a major controlling factor, then the magnitude of fracture permeability should correlate with the contrasting regional stress regimes of the western United States. One means of investigating this possibility is through the use of heat-flow measurements, which have a well-documented sensitivity to fluid flow. Over the past 30 years, the USGS has measured near-surface heat flow in more than 200 holes in the crystalline bedrock of Arizona, California, and Nevada. Repeated temperature logs and closely spaced thermal conductivity measurements in these holes, typically 100 to 250 meters deep, provide useful information on the magnitude and orientation of fluid movement. The thermal data from California reveal that in the region dominated by the compressional and strike-slip tectonics of the San Andreas fault system fewer than 5% of the sites have thermal anomalies within the logged interval which are most likely due to ground-water flow. In the regions dominated by the extensional and strike-slip tectonics of the Basin and Range and the Salton Trough, nearly 30% of the sites show thermal evidence of ground-water flow. The tentative conclusion from these observations is that the difference in magnitude of the least principal effective stress between a compressional and an extensional environment (probably less than 5 MPa in the upper 250 meters) is reflected in the pattern of ground-water flow in fractured crystalline rocks. However, many other factors that can vary on a regional basis, including fault and fracture spacing, the age and frequency of recent tectonic events, local stress perturbations, and fluid chemistry, may also affect the results. If the correlation of regional stress regimes with shallow fluid movement holds, field studies of fluid movement in crystalline rock (e.g., those involving geothermal
exploration, development of water resources, and the tracking of subsurface contaminants) should routinely incorporate investigations of the regional and local stress field. A review of thermal data from Arizona and Nevada will provide additional constraints on the relationship between enhanced ground-water flow and extensional tectonics.

Long Valley Exploratory Well. To prepare for Phase III of drilling of the Long Valley Exploratory well, the Phase II (13 3/8") liner was tied back to the surface and the annulus was completely cemented in. The Phase II corehole (2.1 to 2.3 km) was plugged with cement, and a new 12 1/4" pilot hole was drilled about 100 m beyond the casing shoe. Injection tests in the newly drilled pilot section between 2080 and 2150 meters indicated sufficient permeability in the Mount Morrison roof pendant to explain the observed low temperatures on the basis of hydrologic recharge. The two-dimensional hydrologic model proposed by Craig Forster (University of Utah) is validated by these data, and the prediction of temperatures approaching 400 C at the Phase III target depth of 4.3 km (also predicted by a seismicity cut-off at 4 km) is strengthened.

Alpine. In collaboration with the State of Arizona and DOE’s Geothermal Division, thermal studies are being carried out in a 1.4 km deep corehole at Alpine Divide south of Springerville, Arizona. From preliminary temperature logs and thermal conductivity determinations on core and cuttings, it appears that earlier estimates of heat flow in a shallower hole by the Arizona Geological Survey were high by as much as 50%. We are currently negotiating with the State of Arizona to take over the well for further studies and for possible deepening.

Geysers Geothermal Field. Temperature and thermal conductivity data were acquired from three idle production wells in the Northwest Geysers. Heat-flow profiles derived from data recorded in the caprock which overlies the steam reservoir reveal a decrease of heat flow with depth in two of the three wells. In the first well, PT30, heat flow decreases from approximately 370 mW/m² near the surface to 300 mW/m² at the base of the caprock (1700 m). In the second well, PT31, heat flow decreases from 450 mW/m² near the surface to 280 mW/m² at the base of the caprock (1600 m). These observations contradict the generally accepted theory that conductive heat flow is constant with depth within The Geysers caprock. There are several possible explanations for this, but the available data suggest that these profiles reflect a local recession or cooling of the reservoir top within the past 5000 to 10,000 years. Near-surface heat flow from PT30 and PT31 exceeds typical values for this part of The Geysers, but the present top of steam in the two wells is similar to regional levels. Thermal recovery following a transient heating event would be consistent with these observations. Although the nature, timing, and magnitude of the event are poorly constrained, it may be related to the evolution of the high temperature (>300°C) vapor-dominated reservoir that underlies the normal (~240°C) vapor-dominated reservoir in the Northwest Geysers.

Thermal Setting of the Parkfield Region. Knowledge of the temperature variation with depth near the San Andreas fault is vital to understanding the physical processes that occur within the fault zone during earthquakes and creep events. Parkfield is near the southern end of the San Andreas fault’s Coast Range segment, which has higher heat flow than the Cape Mendocino segment to the northwest or the Mojave segment to the
southeast. Boreholes were drilled specifically for the Parkfield experiment or converted from other uses at 24 sites within a few kilometers of the San Andreas fault near Parkfield. These holes, which range in depth from 150 to over 1500 m, were used mainly for the deployment of volumetric strain meters, water-level recorders, and other downhole instruments. We obtained temperature profiles from all of these holes, and we were able to estimate heat flow at 16 sites. For a number of reasons, primarily a paucity of thermal conductivities and rugged local topography, the accuracy of individual determinations was not high enough to document local variation in heat flow. Heat flow ranges from 60 to 90 mW m$^{-2}$, with a mean and 95% confidence limits of 74±3.5 mW m$^{-2}$, respectively. This is somewhat lower than the values of 83±2.5 for 39 previously published heat flows from the Coast Range segment of the San Andreas fault zone, but it is consistent with the regional broad zone of elevated heat flow with low values east of the fault in the Great Valley and the Sierra Nevada. The low heat flow close to the fault emphasizes the absence of a frictional thermal anomaly there and provides additional support for the notion of nearly fault-normal maximum compressive stress and a small component of shear stress along the fault.
Reports:


This study has focused on the recovery of Hayward fault Paleoseismic data from trench exposures at Tule Pond in Fremont. The investigation is designed to recover temporal evidence of seismogenic movement of the Hayward fault's southern segment. Five trenches excavated across the fault reveal evidence for a minimum of six Hayward fault ruptures during the past \( \leq 2100 \) years.

The detailed layering of the Tule Pond deposits has provided a unique opportunity to document the timing of the southern Hayward fault's recent slip. Current radiometric data from this study indicate that the fault's past ruptures occurred, on average, every 150-250 years. This appears to support the 167-year average recurrence estimated in published earthquake forecasts. Significant gaps exist in the sedimentary record at Tule Pond, thus some late Holocene ruptures may not be recorded at this site. Intriguingly, qualitative data also appear to record some very short recurrence periods. Age interpretations are based on the youngest suite of many AMS radiocarbon analyses. It is assumed that the youngest dates best represent unit ages. Additional age constraints are expected from ongoing radiocarbon analyses.

A final trench at Tule Pond is scheduled for May 1994. This trench will optimize findings from trenches W1 and W2 excavated across the eastern Hayward fault trace to the south of Walnut Avenue. Trench W3 was delayed due to access negotiations for the final site. We anticipate renewed access to the site for Spring/Summer 1994.

**Strawberry Creek, Berkeley**

In the course of these investigations we have identified a site that records a long-term, high-confidence average slip rate for the northern Hayward fault. Motion of the Hayward fault is recorded by the 335±30 m displacement of the active course of Strawberry Creek, a large competent stream draining the Berkeley Hills adjacent to the University of California, Berkeley. Former drainages of Strawberry Creek have been offset even greater distances (Buwalda, 1929; Williams and Hosokawa, 1992). The most recently "beheaded" drainage of Strawberry Creek, the "Mining Circle channel" is offset 580±35 m from its source at Strawberry Canyon.

Williams and Hosokawa (1992) argued that the present 335 m offset of Strawberry Creek accumulated subsequent to abandonment of Mining Circle channel. If we accept the 9±2 mm/yr slip rate estimated by the WGCEP (1990), Mining Circle channel abandonment occurred about 35,000 years before present. The power of the Mining Circle channel age to effect earthquake hazard calculations is illustrated as follows: a 2 mm/yr change in the true average slip rate is recorded as a 10,000 year difference in abandonment age, and is therefore easily distinguished by radiometric dating (with counting uncertainties equivalent to ±50 years). But a 2-mm/yr
change in average slip rate produces a large change in the WGCEP recurrence estimate. For example, the stated WGCEP slip rate uncertainty generates median recurrence intervals that range from 135 to 215 years! Uncertainty of channel geometry, estimated conservatively, contributes a maximum of 12% to the uncertainty of the long term rate. Additional landform data is available from the grading plans for Memorial Stadium, and may reduce geometric uncertainty. Recovery of accurate slip-rate data, over a period of ca. 150-200 earthquake cycles, would increase the credibility of calculated Hayward fault recurrence behavior.

Deposits of the Mining Circle channel were exposed in the during construction in 1992 and revealed the presence of coarse channel deposits. The timing of stream abandonment can be recovered from careful exhumation and analysis of fluvial and colluvial material in the buried deposits of the Mining Circle channel. Re-excavation of the site is logistically feasible during the ongoing construction, but is not currently planned.

References:
Williams, P.L. and A.M. Hosokawa, 1992, Geomorphic features related to the Hayward fault at the University of California at Berkeley, in Taylor, C.L., Hall N.T. and Melody, M. eds., Field Trip Guidebook, Second Conference on Earthquake Hazards of the Eastern San Francisco Bay Area, Hayward State University, 65-71.
CYCLIC STICK-SLIP, FLUID TRANSPORT AND  
THE EARTHQUAKE CYCLE  

**USGS Grant #143493-G2279**  
Program Element 1.1  

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**Objectives**

A physical understanding of stick-slip instability as an analogue of earthquake rupture is of fundamental importance to earthquake mechanics. To this end, laboratory studies on rock friction can elucidate the friction constitutive relation, the micromechanics of frictional sliding and their relation to stick-slip instability behavior. An objective of the present study is to investigate the mechanics of shear localization in fault gouge in relation to the development of stick-slip instability. To explain fault normal compression and apparent weakness of the San Andreas fault system, several models for the generation and maintenance of pore pressure excess in a seismogenic zone were recently proposed. To better constrain these models especially with regard to the possible transition from hydrostatic pore pressure near the surface to nearly lithostatic pore pressure at depth, systematic investigation of the dependence of permeability of fault gouge on stress and loading path is necessary. A second objective of the present study is to conduct experimental investigation of the physical processes controlling the reduction of permeability in fault gouge, especially in relation to the compaction mechanism, gouge mineralogy, grain size distribution and porosity.

**Development of Riedel shear localization in simulated quartz gouge**

Frictional sliding experiments were conducted on two types of simulated quartz gouge (with median particle diameters 5 μm and 25 μm respectively) at confining pressures ranging from 50 MPa to 190 MPa in a conventional triaxial configuration. To investigate the operative micromechanical processes, deformation texture developed in the gouge layer was studied in samples which had accumulated different amount of frictional slip and undergone different stability modes of sliding. The spatial patterning of shear localization was characterized by quantitative measurement of the shear band density and orientation. Shear localization in the ultrafine quartz gouge initiated very early before the onset of frictional sliding. Various modes of shear localization were evident, but within the gouge zone R₁-shears were predominant. The density of shear localization increased with cumulative slip, whereas the angle subtended at the rock-gouge interface decreased. Destabilization of the sliding behavior in the ultrafine quartz gouge corresponded to the extension of R₁-shears and formation of boundary Y-shear segments, whereas stabilization with cumulative slip was related to the coalescence of Y-shear segments to form a
throughgoing boundary shear. In the coarse quartz gouge, the sliding behavior was relatively stable, probably because shear localization was inhibited by distributed comminution.

Two different models were formulated to analyze the stress field within the gouge zone, with fundamentally different predictions on the orientations of the principal stresses. If the rock-gouge interface is assumed to be bonded without any displacement discontinuity, then the maximum principal stress in the gouge zone is predicted to subtend an angle greater than 45° at the interface. If no assumption on displacement or strain continuity is made and if the gouge has yielded as a Coulomb material, then the maximum principal stress in the gouge zone is predicted to subtend an angle less than 45°. If the apparent friction coefficient increases with overall slip (i.e. slip-hardening), then the Riedel shear angle progressively decreases with increasing shear strain within the gouge layer, possibly attaining a zero value which corresponds to a boundary Y-shear. Our quantitative data on shear localization orientation are in reasonable agreement with this second model, and implies that the coefficient of internal friction to be about 0.75 for the ultrafine quartz gouge and 0.8 for the coarse gouge. The wide range of orientations for Riedel shear localization observed in natural faults suggests that the orientations of principal stresses vary as much as in an experimental gouge zone. The detailed results are presented by Gu and Wong [1994].

**Compaction-induced permeability reduction and the development of pore pressure excess**

Permeability exerts significant control over the development of pore pressure excess in the crust, and it is a physical quantity sensitively dependent on the pore structure and stress state. In many applications, the relation between permeability and effective mean stress is assumed to be exponential and that between permeability and porosity is assumed to be a power law, so that the pressure sensitivity of permeability is characterized by the coefficient \( \gamma \) and the porosity sensitivity by the exponent \( \alpha \). We review our experiments and other published data on intact rocks, unconsolidated materials and rock fractures. The permeabilities of tight rocks and rock joints show relatively high pressure sensitivity and low porosity sensitivity. A wide range of values for \( \alpha \) and \( \gamma \) have been observed in relation to the mechanical compaction of porous rocks, sand and fault gouge, whereas the porosity sensitivity for chemical compaction processes is often observed to be given by \( \alpha=3 \). Since the ratio \( \gamma/\alpha \) corresponds to the pore compressibility, the different dependences of permeability on porosity and pressure are related to the pore structure and its compressibility.

Guided by the laboratory data, we conduct numerical simulations on the development of pore pressure in crustal tectonic settings according to the models of Walder and Nur [1984] and Rice [1992]. Laboratory data suggest that the pressure sensitivity of fault gouge is relatively low, and to maintain pore pressure at close to the lithostatic value in the Rice model, a relatively high influx of fluid from below the seismogenic layer is necessary. The fluid may be injected as vertically propagating pressure pulses into the seismogenic system, and Rice's [1992] critical condition for the existence of solitary wave is shown to be equivalent to \( \alpha>1 \), which is satisfied by most geologic materials in the laboratory.
Laboratory data suggest that the porosity sensitivity is relatively high when the permeability is reduced by a coupled mechanical and chemical compaction process. This implies that pore pressure may be generated in a crustal layer more efficiently than cases studied by Walder and Nur [1984], who assumed a relatively low porosity sensitivity of $\alpha$=2. The detailed results are presented by David et al., [1994].

**Ongoing experimental studies**

Simulated gouges of different mineralogies have been prepared, and their particle size distributions are characterized by standard sieve technique. Frictional sliding experiments will be conducted on sawcut sandstone samples sandwiched with the gouges using our servo-controlled triaxial apparatus. Permeability of the gouge layer will be determined as a function of the mean stress and shear strain. The development of shear-induced microstructure and deformation fabric in the gouge layer will be characterized quantitatively, and the relation to permeability evolution will be investigated.

**Publications**


Active Faults and Folds in the Salem Metropolitan Area, Oregon

Agreement No. 14-08-0001-G2131

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Investigations

Paul Crenna and Robert Yeats completed an analysis of subsurface and surface geological data in the Waldo Hills, Salem Hills, and Stayton Basin east and south of Salem. A tectonic map of this region is shown as Figure 1. Structure contour maps were prepared of the base of Columbia River Basalt Group, top of Columbia River Basalt Group, and the base of Pleistocene outwash gravels, and isopach maps of the Columbia River Basalt Group and fine-grained alluvial deposits overlying the basalt. Cross sections across the Stayton Basin and Waldo Hills and profiles of the North Santiam and Willamette Rivers were prepared. This work was done in coordination with Scott Burns of Portland State University, who conducted a subsurface study of the Salem East and Salem West 7 1/2 minute quadrangles, and with Marshall Gannett of USGS Water Resources, who completed an ArcInfo-based aquifer study of the Willamette Valley.

The fine-grained alluvial deposits of the Willamette Valley are the youngest sediments known to be cut by crustal faults, and Shaul Levi worked out the magnetic stratigraphy of two core holes near Salem that were continuously cored by the Oregon Department of Transportation at no cost to our project.

Results

1. The Waldo Hills are tectonically uplifted by flanking faults that cut the older Willamette Valley alluvial deposits; these are the Waldo Hills fault on the north and the Mill Creek fault on the south. Both faults appear to lose separation eastward, although the pronounced linear trend of the northern range front of the Waldo Hills continues for another 30 km to the NE, as far as the epicenter of the 1993 Scotts Mills earthquake. The Waldo Hills fault is closest to Salem and thus poses an earthquake hazard that should be taken into consideration in zoning and building construction in Salem.

2. The Stayton basin is a tectonic depression with several hundred meters of tectonic relief on the top of the Columbia River Basalt Group. The Salem and Eola Hills are tilted east, but this tilt is most pronounced in the southern Salem Hills directly west of the Stayton basin. The basin may have formed as a pull-apart basin between the East Albany and Mill Creek faults; if so, these faults would have a strong component of left-lateral strike slip. However, we have no independent evidence for left slip on either of these faults, although the Corvallis fault, also with a NE strike, has some suggestion of strike slip near the city of Corvallis.
The alluvial sequence overlying the Columbia River Basalt Group consists of a lower, predominantly fine-grained unit and an upper unit consisting primarily of gravel, at least in part Pleistocene based on magnetostratigraphy. Mill Creek water gap between the Salem Hills and Waldo Hills was probably cut by the North Fork Santiam River, which now flows around the south end of the Salem Hills. The lower boundary of the gravel unit is 60 m lower on the north side of the Waldo Hills than it is on the south. In the Salem water gap, the slope of the base of the gravels is 20 times steeper than that of the channel of the modern Willamette River, possibly due to pre-gravel rapids generated by uplift of the Salem-Eola Hills monocline. If the gravels were glacially derived, this uplift would be latest Pliocene to Pleistocene.

3. Both the Sublimity and Corvallis core holes yielded remanent magnetic polarity, showing that paleomagnetic study is a useful method for dating the overbank alluvial deposits. The Sublimity core hole provided the best results, in part because pollen analysis by Cathy Whitlock of the University of Oregon gave evidence that the sediments were deposited in a climate much colder than today, indicating an age younger than 2.5 Ma, the age of initiation of the ice ages. Accordingly, the predominantly reversed-polarity section at Sublimity can be referred to the Matuyama Chron and dated as Pleistocene. However, the two core holes cannot be correlated with each other paleomagnetically, indicating that dating the entire Willamette Valley overbank sequence will require paleomagnetic study of many more core holes as well as the exposed Sandy River Mudstone east of Portland. Calibration of the magnetic stratigraphy by pollen analysis is necessary to demonstrate that the sediments are Pleistocene and to offer the potential of determining sediment accumulation rates and slip rates of faults cutting the section, in particular the Mt. Angel fault that produced the 1993 Scotts Mills earthquake.

4. Even though the Scotts Mills earthquake ruptured a known fault, it produced no surface rupture. We still have no evidence for Holocene displacement on any of the faults we have identified in the Willamette Valley. For the most part, the faults we have identified are relatively short, some with lengths less than the thickness of brittle crust. Therefore, earthquakes along such faults may be relatively small, in the magnitude range 5 to 6, like those at Scotts Mills and at Portland in 1962, and they may not rupture through to the surface. The vertical component of slip rate on these faults must be very low, a fraction of a millimeter per year. If so, the repeat time for Scotts Mills-type earthquakes on the same section of fault may be measured in tens of thousands of years. However, because the earthquake ruptured such a small section of fault, and there are so many faults that have the potential for rupture, we should plan our zoning and building construction as though we would experience a Scotts Mills-type earthquake on one of these faults every few decades, well within the life of an average building.

5. The Waldo Hills and Mill Creek faults line up with the Corvallis fault, producing a NE-trending lineation nearly 100 km long. The Corvallis fault does not connect with the Waldo Hills structures at the surface, but if it connected at
depth, rupture of the entire lineament simultaneously could produce an
earthquake of M 7.

Report

Crenna, P. A., Yeats, R. S., and Levi, S., 1993, Neogene and Quaternary tectonics
of the Salem metropolitan area, Oregon, west of the 1993 Scotts Mills
FIGURE 1 Neotectonic map of the Salem metropolitan area showing structures which deform the Columbia River Basalt Group. The Corvallis fault, East Albany fault and Scotts Mills anticline are shown for reference only: evidence of post-CRBR activity on these structures is inconclusive.
REGIONAL AND LOCAL HAZARDS MAPPING IN THE EASTERN GREAT BASIN

9950-01738

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INVESTIGATIONS

1. Began study of the neotectonic deformation field associated with diapiric emplacement of shale in the Salina, Utah area.

RESULTS

1. Several kilometers of contacts between Jurassic Arapien shale and overlying Tertiary rocks are shown on published maps as depositional contacts but are actually fault zones above which Tertiary strata are generally structurally attenuated. The attenuation partially accommodates for diapiric upwelling of shale into lobate culminations along the Sevier-Sanpete anticline. The fault zones mark the boundaries of the diapirs. Motion indicators in these fault zones, as well as drag folds adjacent to them, commonly show important components of previously unrecognized strike slip. We are investigating the structural interaction between the diapirism and the strike-slip translations because the resulting strain field has many features in common with footwall uplifts and fault segmentation along major potentially hazardous faults such as the Wasatch and Hurricane. There are also structural parallels with other range blocks in the eastern Great Basin as well as with metamorphic core complexes in extensional terranes in general. Our study should result in an improved understanding of the relationship between brittle faulting and ductile or semiductile flow in extensional regimes.

REPORTS


Introduction

We utilize nearly identical microearthquake pairs recorded by the Anza, Parkfield, and Southern California seismic networks as quasi-repeating broadband sources at depth to probe seismic gaps in California for possible temporal variations in the seismic Green function. Significant progress has continued the past year on the three principal goals of this project:

1. Comprehensive identification of similar earthquake pairs and clusters in large microearthquake data sets.
2. Development and evaluation of techniques for relative waveform analysis.
3. Analysis of similar microearthquake seismograms to identify or establish limits on temporal variability in seismic Green's functions, specifically concentrating on seismic velocity, coda decay, and shear-wave anisotropy.

Progress

Comprehensive identification of similar earthquakes in large microearthquake data sets.

The first step in the project, now completed, has been to develop and apply algorithms for comprehensively identifying earthquake pairs and clusters most suitable for similar earthquake analysis. This work has recently been published showing results from the Anza seismic network spanning October, 1982 through April, 1992. (Aster and Scott, 1993; Figure 1a). The technique has also recently been applied to the Parkfield High-resolution Seismic Network data set (Figure 1b), and we are in the process of organizing Southern California Seismic Network data from the Landers area for a similar analysis. A highly remarkable aspect of the study to date is the much higher occurrence of extremely similar events at Parkfield relative to Anza.

Development and evaluation of techniques for relative waveform analysis.

The signal processing aspects of similar earthquake analysis generally involve two overlapping concerns. 1) Temporal alignment (or equivalently, lag estimation), either in moving windows or for entire seismograms. This type of measurement is especially appropriate for analyzing possible velocity variations in direct body phases and possibly for secondary phases buried in the coda (e.g., Verwoerd et al., 1992, Elsworth et al., 1992; Scott et al., 1993).

2) Estimation of moving-window spectral ratios. This technique is most appropriate for coda analysis, where one is testing for smooth variations in the Green function frequency response, such as might be induced by temporal variations in the degree of lithospheric scattering. Much recent work in this regard has concentrated on obtaining optimal moving window spectral ratio estimates with reasonable, nonparametric error bounds for use in relative coda analysis.

Analysis of similar microearthquake seismograms to identify or establish limits on temporal variability in seismic Green's functions.

Identifying Temporal changes in seismic velocity. If temporal changes in seismic velocity exist due to stress-induced changes in or near the fault zone, they may be detectable in the variation of
Figure 1. a) Earthquake similarity (median waveform crosscorrelation) versus interhypocenter separation for Anza network seismograms recorded between 1982 and 1992 (4569 events: 1,121,332 comparisons: search radius of 10 km: after Aster and Scott, 1993). b) Earthquake similarity (median waveform crosscorrelation) versus interhypocenter separation for Parkfield HRSN seismograms recorded between 1987 and 1992 (3043 events: 1,221,201 comparisons: search radius of 7.5 km).
travel time residuals for rays which sample the same region at different times (Poupinet et al., 1984; 1985). Signals from nearly identical earthquakes in the Anza similar event catalogue are ideal for this type of analysis as differences due to path and source differences will be minimized. Scott et al. (1992; 1993) analyzed highly similar pair of events identified by Aster and Scott (1993). The long-term changes in seismic travel times, as measured from the pairs with the longest time separation are not significantly greater than the noise level estimated from short-time separation event pairs. Almost all P-wave paths show less than 0.06% changes in travel time, and all S-wave paths have less than 0.03% changes in travel times. There is thus no evidence from these ray paths that any long term accumulation of stress in the region is affecting the seismic velocities.

Identifying Temporal changes in seismic coda. Coda $Q$ offers perhaps the best hope for finding temporal changes in Earth response associated with the earthquake cycle. Besides having a “large footprint” advantage of sampling a large volume and thus possibly being more sensitive to small, but regional changes in Earth properties, coda analysis is especially intriguing because numerous reports exist in the literature of reported temporal variations, some of which were precursory to large earthquakes (see Sato, 1988; Wyss et al., 1991). Regions with reported temporal changes include the Anza area; Haar (1989) analyzed 37 earthquakes recorded by the Anza network between June, 1984 and December, 1987 and reported an intriguing increase (at a confidence level of greater than 0.99) in the coda decay rate observed Anza network station KNW. This study noted an anomalously high attenuation, for earthquakes occurring in the 18 months before the North Palm Springs earthquake. A similar conclusion was reached by Su and Aki (1990) examining SCSN data.

Because of the intriguing possibility of distributed lithospheric temporal changes which may affect coda signals from similar earthquakes with long-time separations, we have spent much of the past year investigating this problem in detail. To estimate the log spectral ratio with accurate error bounds and a minimum of spectral leakage, we utilize multitaper algorithms (Thomson, 1982; Park et al., 1987) with adaptive weighting of the $k$ individual spectral estimates for each portion of subsample-aligned similar earthquake time series. The resulting matrix of log spectral ratio values as a function of time and frequency, averaged over three components, $r(f, t)$, and the matrix of standard deviations, $\sigma$, are then used to obtain parameters characterizing both relative source differences and relative differences in coda $Q$, $Q_c$, using the Aki and Chouet (1975) model, which predicts a seismic coda of the form:

$$A(f, t) = S(f) t^{-m} e^{-\pi f t / Q_c(f)}.$$ 

The relative log spectral ratio between two events with identical scattering footprints is thus (e.g., Got et al., 1990; Got and Fréchet, 1992)

$$r(f, t) = \ln \left[ \frac{A_1(f, t)}{A_2(f, t)} \right] = \pi \Delta Q_c^{-1}(f) ft + \ln \left[ \frac{S_1(f)}{S_2(f)} \right] = V(f, t) + W(f)$$

where the difference in coda $Q$ is codified in the time and frequency dependent term, $V(f, t)$, as

$$\Delta Q_c^{-1}(f) = \frac{1}{Q_{c2}(f)} - \frac{1}{Q_{c1}(f)}$$

and the difference in the source spectral ratio is given by

$$W(f) = \ln \left[ \frac{S_1(f)}{S_2(f)} \right].$$

Using the above formalism, $\Delta Q_c^{-1}$ and $W$ can be estimated within a particular frequency band, centered on $f$, from the observed parameters and their respective standard deviations by solving the weighted linear overdetermined system of equations.
In accordance with the assumptions of the Aki-Chouet model, only times greater than twice the S-wave travel time to the station are used. To obtain estimates for frequency-dependent $\Delta Q^{-1}_c$, the system is inverted for successive frequency bands. To accurately reflect the uncertainty in the multitaper, log spectral estimate estimates, confidence intervals are estimated using a Monte Carlo approach (e.g., Press et al., 1988) Figure 2 shows applications of the algorithm to synthetic and real data. For testing purposes, synthetics were generated from high-correlation, band-limited, Gaussian white noise (Figure 2a). Many instances of Anza seismograms show some departures from zero $\Delta Q^{-1}_c(f)$, which is not unexpected given the extreme simplicity of the Aki-Chouet model (Figure 2b). We are presently concentrating on testing for systematic behavior in these determinations to see if statistically significant variations exist in the Anza and Parkfield data sets. An additional aspect of this work involves investigating tradeoffs between $W(f)$ and $V(f, t)$. As with our study of velocity stability, short-time base similar event pairs are again useful in establishing the noise level of the process.

### Summary.

We have completed the development of a similar event identification and classification algorithm suitable for analysis of even the largest presently-existing microearthquake data sets. This algorithm, along with the application to Anza network data has been recently published (Aster and Scott, 1993). New results include the successful application of the technique to data from the Parkfield High Resolution Seismic Network (Aster et al., 1993). A current major effort is to apply this technique to the particularly intriguing Landers/Big Bear region microearthquake data set recorded by the Southern California Seismic Network from 1982 to present, which will enable us to test for both preseismic and coseismic variability in Earth parameters.

A reliable, well-tested algorithm has been perfected for assessing variability in $Q_{coda}$. This algorithm is currently being comprehensively applied to data from the Anza and Parkfield data sets. This technique will also be applied to the Landers data set when the similar events identification procedure now in progress is completed.

### Reports, Papers and Presentations Associated with this Project.


Additional References


Figure 2a. Synthetic example illustrating the inversion of moving-window log spectral ratio data for the log source spectral ratio, $W(f)$, and the apparent change in inverse coda $Q$, $\Delta Q^{-1}(f)$. The dashed lines on the $W(f)$ and $\Delta Q^{-1}(f)$ plots are theoretical values. Error bars are 68.3% confidence intervals. Figure shows the observed spectral ratio (upper left) and its standard deviations (lower right); the spectral ratio predicted by the model (upper right); the residual (lower right); and the model parameters (bottom). The title shows the data length used (DLEN), the broadband crosscorrelation (C), the number of multitaper windows used (NW), the length of the moving 75% overlap time windows (WLEN), and the spectral bandwidth (BW).
Figure 2b. Anza network example illustrating the inversion of moving-window log spectral ratio data for the log source spectral ratio, $W(f)$, and the apparent change in inverse coda $Q$, $\Delta Q^{-1}(f)$. As with Figure 2a, modeling is performed at times greater than twice the shear-wave arrival time, shown by the vertical line. Low signal-to-noise data (white regions) is not used in the parameter determination.
Program Element: II

Holocene Paleoseismology in Western Washington State

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Investigations and Results:

New research under this project in 1993 consisted mainly of field studies of prehistoric liquefaction features along tidal reaches of the Columbia River. These features provide the first strong evidence that inland shaking accompanied coastal subsidence along the Cascadia subduction zone about 300 years ago.

The discovery of the liquefaction features, made in 1992 by Steve Obermeier of the USGS in Reston, raised hopes of testing independent inferences that great (magnitude 8 or 9) earthquakes have occurred along the Cascadia subduction zone. Detailed studies began in the summer of 1993: surveys of 200 features in 11,000 m2 of low-tide outcrop along 2.7 km of riverbank among six islands 30-60 km inland from the coast; standard penetration measurements at 50 sites among the surveyed banks; and vibracoring at 9 of the standard-penetration sites. Important contributors to this work included Catherine Chatfield and Coby Menton (field assistants), John Shulene and Boyd Benson (volunteers), Steve Palmer (Washington Division of Geology and Earth Resources), Lynn Moses (Washington Department of Transportation), Tim Roberts (Oregon Department of Geology and Mineral Industries), Steve Dickenson (Civil Engineering, Oregon State University), and Curt Peterson (Geology, Portland State University). The National Oceanic and Atmospheric Administration contributed an excellent work boat with a fickle motor.

Most of the liquefaction features are dikes exposed at low tide near the level of a pair of marker beds. Such dikes crop out in wave-washed banks of Marsh and Brush Islands (33-34 km east of the coast), Price and Hunting Islands (44-45 km), and lower Wallace Island (57 km). Additional, probably correlative dikes can be seen in banks without the pair of markers at upper Wallace Island (59 km) and at Deer Island (90 km; 15 km west of the longitude of Portland). The width of the largest dike noted is 30 cm at Marsh and Brush Islands, 8 cm at Price, 20 cm at Hunting, 5 cm at lower Wallace, 15 cm at upper Wallace, and 10 cm at Deer. Still wider dikes have probably been lost to erosion, which has narrowed most of the surveyed islands >100 m in the past 120 years.

Four lines of evidence--described in an abstract by Obermeier and others (1993)--together suggest that the liquefaction resulted from a subduction-zone earthquake that caused
coastal subsidence about 300 years ago: (1) Sand vented at Marsh Island at or about the
most recent time when the island subsided, which was >200 years ago. (2) Sand vented
at Price Island <380 years ago. (3) The highest dikes at Marsh, Brush, Price, Hunting, and
lower Wallace Islands cut a tephra layer probably 500 years old. (4) Many of the dikes at
Marsh, Price, Hunting, and lower Wallace Islands cut deposits less than 1000
radiocarbon years old.

Engineering studies of the liquefaction features may eventually place lower bounds on
earthquake magnitude. Initial estimates by Palmer and Dickenson show that the
earthquake 300 years ago exceeded magnitude 7.

Reports:

along the Cascadia subduction zone [abstract]: Eos, v. 74, no 43, p. 199-200.

Obermeier, S.F., Atwater, B.F., Benson, B.E., Peterson, C.D., Moses, L.J., Pringle, P.T., and
Palmer, S.P., 1993, Liquefaction about 300 years ago along tidal reaches of the
Columbia River, Oregon and Washington [abstract]: Eos, v. 74, no. 43, p. 198-199.
Crustal Deformation Measurements in the Shumagin Seismic Gap, Alaska

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Program Element: II.3 Grant 14-08-0001-G1792

Investigations Undertaken

1. Twelve short (~ 1 km) level lines are measured every one to three years within the Shumagin Islands seismic gap, Alaska (Figure 1). Surface tilt data are interpreted in terms of tectonic deformation and earthquake hazard at the Pacific-North American plate boundary. Most of these level lines (and all those with the longest histories) lie in the eastern third of the seismic gap where the Shumagin Islands themselves are located.

2. Six absolute-pressure sea-level gauges (Figure 1) are operated in the Shumagin Islands in order to measure differential vertical deformation associated with the Aleutian subduction zone.

3. Some of the sea-level data are transmitted by satellite in near real time, and are examined for possible tectonic signals. Noise studies are used to determine the relative usefulness of different types of measurement, and to evaluate the minimum size of tectonic signal visible above the noise. Our data are compared with other crustal deformation data from the Shumagin gap.

4. In cooperation with USGS Menlo Park scientists, we are making GPS survey measurements in the Shumagin Islands. With support from NASA's Dynamics of the Solid Earth program, these measurements were extended east and west of the Shumagin Islands during 1993. Over the next few years the GPS measurements, supported jointly by USGS and NASA, will allow us to examine important questions about the variability in the deformation field along the strike of the arc.

Results (December 1993)

May 1993 Earthquakes

The major event of the year was a May 13, 1993 magnitude 6.9 earthquake (as big as the Loma Prieta event) within the Shumagin Islands. Because of this earthquake we altered our field plans somewhat in order to remeasure, using GPS, all but 3 stations of the 18-station EDM (electromagnetic distance measurement) trilateration network established by Jim Savage's group at Menlo Park in 1980, and measured by them through 1987. We also reoccupied the 7 GPS stations (all but 2 co-located with EDM sites) that were measured by the Menlo Park group between 1987 and 1991. The effects of the earthquake, which occurred between the Central and Outer Shumagin Islands (Figs. 1b, 2), were seen clearly in the EDM/GPS histories and in our leveling and sea level histories (Figs. 3, 4, 5).

Figure 2 shows a preliminary solution for the fault plane of the earthquake based mainly on the EDM/GPS data and the Saddlers Mistake (SAD) and Chernabura (CHN1, CHN2) leveling data. The fault plane is constrained to pass through the seismologically determined depth [Triep, pers. comm.; Abers et al., 1993] and location [Jaume, pers. comm.;
of the main shock, and to have the dip of the main shock rupture plane [Abers et al., 1993]. The pattern of deformation at the easternmost stations (Insula, Little, Simeon) suggests that the rupture was confined to the south-west of these stations, and therefore did not break the whole of the "1917 segment" [Boyd et al., 1988].

There remains additional work to do on the dislocation modelling, principally because the 1991 and 1993 GPS positions of Sand Point have not yet been tied to the same consistent global reference frame. This means that the horizontal deformation data presently suffer from a uniform translation ambiguity: relative displacements of points are correct but an arbitrary uniform vector could be added to all the displacement data in Fig. 2. This should not much affect the dislocation model we have derived since that is based on the relative displacement data; however, it will provide an added constraint on the model.

Figure 1a. Location of the Shumagin Islands with respect to the trench and the volcanic arc. Depth contours are in metres. The seismic gap stretches from approximately Sanak Island in the west to about 30 km east of the Shumagin Islands. Also shown are the sites of six sea-level gauges operated by LDGO and one by the National Ocean Survey (at SDP). Level lines of approx. 1 km aperture are located on many of the Shumagin Islands, and on Sanak Is.

Figure 1b. The Shumagin Islands, showing the locations and directions of first-order level lines, whose lengths vary between 600m and 1200m. The resultant of the data from lines SDP and SQH is used to estimate the tilt direction in the Inner Shumagins. The resultant of SIM and SMH is used for Simeonof Island. The lines at CHN and PRS each consist of two approximately straight sections in different azimuths, with benchmarks at the junction. This non-linear geometry allows tilt direction to be estimated at these sites. Two sets of perpendicular level lines have also been installed on Sanak Island, at the western end of the seismic gap (see Fig. 1a). One of these, at the SE end of the island was measured in 1988, 1990 and partially in 1992. The other, at the NW end, was first measured in 1990.

**Level Lines**

Data from level lines measured between 1980 and 1992 (Figure 3) show a consistent pattern of deformation consisting of arcward tilting in the Outer Shumagin Islands and trenchward tilting in the Central and Inner Islands. Some apparently anomalous data from 1991 were not verified by the 1992 measurements. We suspect that the anomalies in some of the 1991 data may be due to the unusually large amount of sunshine experienced during the 1991 field trip, leading to less favourable leveling conditions than normal. The Sanak Island
Figure 2. Horizontal displacements observed (dark lines with 1 $\sigma$ error ellipses) and predicted by a preliminary dislocation model of the fault (light lines). The triangles show locations of EDM, GPS, sea level and level line sites. EDM and GPS sites are named. The rectangle shows the surface projection of the fault plane. Parameters of the fault are length=60 km, width=34 km, depth to bottom=48 km, dip=26°, strike=60°, rake=90° (pure thrust), slip=0.5 m. The resulting static seismic moment is $3.1 \times 10^{19}$ Nm, some 15% higher than the Harvard CMT estimate. This model also fits well the leveling data from SAD and CHN (see Fig 1b for locations). The epicenters of the May 13 main shock and May 25 aftershock are also shown.
Figure 3. 1980-93 leveling history from the Outer (above), Central (left) and Inner (below) Shumagin Islands. Tilt rates, 1 sigma error bars and goodness-of-fit statistics are shown for linear fits to the 1980-1992 data only. Offsets of the 1993 data from these trends represent the effects of the May 13, 1993 quake (plus noise). Earthquake effects are particularly noticeable on lines CHN2 and SAD. Upward trends imply relative ground uplift in the direction given in the plot title. Tilting prior to the quake was arcward in the Outer Islands, and trenchward in the Inner/Central Islands.
level lines were partially remeasured in 1992, and the data (Fig. 3b) do not corroborate the substantial tilt rate suggested by the 1988-90 measurements.

![Figure 3b](image)

Figure 3b. 1988-92 leveling history from the level lines at Salmon Bay, S.E. Sanak Island. See Figure 3a caption for details. The data do not currently indicate the presence of high tilt rates at these sites.

The May 1993 earthquake signature was in the opposite sense to the 1980-92 trends on all lines that were repeated in 1993, suggesting that we are observing strain build-up and release associated with moderate-sized earthquakes in the Shumagin region.

There is observable 1992-93 signal on two lines (SDP and SQH, Fig. 3) in the Inner Shumagins that is not fit by the model shown in Figure 2. To fit these data would require deeper and more arcward slip on the plate interface, which might then violate other deformation constraints. This has not yet been fully investigated. However, the signal at SQH is marginal, and the south end of the SDP level line, while on bedrock, is within about 100 m of major earthworks associated with reconstruction of the Sand Point runway. It is conceivably that elastic unloading associated with the removal of large quantities of rock could have caused the SDP signal - this will be investigated further.

**Differential Sea Level**

All available differential sea level data from the 1976-93 period have been analyzed. Results from the sites with the longest history are shown in Figure 4. Each plotted point represents the average sea level difference over a 3 month interval. If the data are interpreted by a constant differential uplift rate between 1976 and 1992, then the Outer Islands appear to have been subsiding relative to the Inner Islands at about 4±1 mm/yr. If only the higher quality post-1986 data are used, there is still an apparent relative subsidence of the Outer Islands at 1.8±1.2 mm/yr. Looking at data from all stations operating since 1981 provides the same general picture: both the Central Islands and the Outer Islands appear to be subsiding at about the same rate, 4±1 mm/yr, relative to the Inner Islands.

The sea level and tilt (leveling) data from 1980 through 1992 are in the same sense as predicted by simple models of strain accumulation at a locked subduction zone [e.g., Savage, 1983], but are almost an order of magnitude smaller. Such motion is consistent with the tilt data derived from leveling for a mode of deformation like that sketched in Fig. 6. These motions are in the same sense as are predicted by simple models of strain accumulation at a locked subduction zone [e.g., Savage, 1983], but are almost an order of magnitude smaller.
SHUMAGIN ISLAND SEA LEVEL DIFFERENCES: 1976-1993

Figure 4.

Data
1976-77: Mean-sea-level-indicator at PRC, SIM. NOS gauge at SDP.
1981-84: Ceramic pressure gauge at PRC, SIM. NOS gauge at SDP.
1985-92: Paros quartz pressure gauge at PRC, SIM. NOS gauge at SDP.

All gauges are periodically tied to local benchmark arrays to check their stability.

Location
SIM is 80 km trenchward of PRC and SDP. PRC and SDP are fairly close together on the same island, and are expected, \textit{a priori}, to show little or no differential motion.

Tectonic Interpretation
If the 1976-92 data are interpreted as constant tilt rate (shown by dashed line and slope printed in larger typeface), then SIM is subsiding relative to PRC/SDP at about 4±1 mm/yr.
If fit is made only to the 1985-92 data (line not shown, but slope printed in smaller typeface), then SIM appears to be subsiding relative to PRC/SDP at about 3±1 mm/yr.
Figure 5. Sea level difference histories for those sites for which we have data both before and after the May 1993 earthquakes. Each point is a 3-monthly mean of the difference data after removing tides, editing outliers, and low-pass filtering the data. An exception is the data points in the second quarter of 1993 for which we have estimated separate mean values before and after the earthquake (top two plots only). Linear fits are made to the data from 1981 until prior to the May 1993 earthquakes. We interpret a fall in differential sea level as a relative ground uplift between the two stations. The principal signal through early 1993 is a steady ground uplift of the Inner Islands (PRC) with respect to both the Central (EGH) and Outer (SIM) Islands (lower two plots). During the earthquake these trends were partially reversed with sites SIM and EGH uplifting with respect to PRC, each by about 3.3 cm. During the earthquake, site SIM subsides by about 1.1 cm with respect to CHN and rises by about 1.1 cm with respect to PRS, but neither of the two latter estimates is significantly different from zero.
All other deformation data collected in the Shumagins have likewise shown rates smaller, sometimes as much as an order of magnitude smaller, than the rates expected on the basis of the simplest model [e.g., Lisowski et al., 1988; Beavan, 1988, 1989, 1990; Ma et al., 1990; Larson & Lisowski, 1994]. A completely satisfactory explanation has not yet been given for the discrepancy between these low deformation rates and the high seismic potential [Boyd et al., 1988; Nishenko and Jacob, 1991] deduced from seismic observations. However, model studies based on coupled elastic/viscoelastic rheologies and partial locking of the plate boundary [Dmowska et al., 1992] appear to offer one route towards understanding this problem.

![Figure 6](image)

**Figure 6.** Cartoon showing type of deformation field that could give rise to the observed 1981-92 tilt and relative uplift signals.

**Effects of May 1993 Earthquakes on Differential Sea Level**

Between 1992 and 1993 the differential uplift was in the opposite sense to the 1981-92 trend for all stations for which we presently have data, as is shown at the end of the SIM-PRC plot in Figure 4, and in more detail in Figure 5. Figure 5 shows differential data from all stations for which we have data both before and after the earthquakes. The 1992-93 offset is determined by fitting a straight line to the pre-earthquake data (1981 to May 1993), extrapolating the fit to later in 1993 and calculating the difference between the observed and extrapolated 1993 values. For differences SIM-PRC and EGH-PRC the pre-earthquake data extend through Dec 1992 and the post-earthquake data start in July 1993. For differences CHN-SIM and SIM-PRS the instruments were running through the earthquake but we currently have data only to the end of June 1993 since the CHN and PRS gauges record their data locally and they will not be downloaded again until June 1994 at the earliest. The post-earthquake sea level differences in these cases are determined from 6 weeks of data following the quake.

We have also attempted to determine coseismic offsets on the CHN-SIM and SIM-PRS records by examining the individual data points either side of the quake. This is a difficult problem because of the usual wave, seiche and weather-related noise in the records and possibly because of the effects of any tsunami resulting from the quake. In this case the tsunami was small [Tanioka et al., 1993] and the offset estimates from this technique are within 50% of the estimates obtained through averaging. We prefer the estimates made from the averaged pre and post earthquake data.
Pre-1980 Leveling Data

Figure 7 plots the complete leveling results from the three level lines with the longest measurement history. In a 1984 paper (Beavan et al., 1984) we interpreted the 1972-82 tilt data. Our interpretation was that the 1972-78 and 1980-82 tilt rates were representative of a locked plate interface, and that the 1978-80 "tilt reversal" was due to an episode of aseismic slip of about 80 cm magnitude on the plate interface.

Our leveling procedures were improved starting with the 1980 measurements. At the time we wrote the 1984 paper we did not believe that the change in procedures had caused a major improvement in the accuracy of the leveling. However, judging by the quality of the data since 1980, we now believe that the 1975-79 data may suffer from systematic errors, so that we are no longer convinced of the reality of the 1978-80 tilt reversal.

Instrument Development: Self-Contained Sea Level Gauges

A self-contained pressure-sensor based sea level gauge has been used since 1990 for recording the sea level data at three of our sites. The instrument can record up to two years of 12-minute sampled data using internal batteries and memory. It is ideally suited to installation in remote, seldom visited areas. Prior to 1990, our only mode of operation was to connect the sensors to onshore electronics via an armoured cable.

The rationale behind these gauges is that they remove the weakest link in our previous system - the electrical cable running through the surf zone from the underwater gauge to the electronics and data transmission system on land. The cable system is being retained at the more sheltered locations (PRC, EGH, SIM) in order to provide near-real-time data from a subset of sites.

Annual recalibrations of the pressure sensor (used in both self-contained and cable gauges) show stabilities at better than the 5 mm level, particularly since 1987 when the manufacturer made significant improvements to the sensor [J. Paros, pers. comm., 1991]. Differential uplift rates with 1σ errors at the 1-2 mm/yr level over 80 km baselines are achievable with 5 years of data.

All three self-contained gauges were recovered in excellent physical condition, both in 1992 and in 1993. In 1991/92 all data were recovered from the instruments with the exception of the last few months at CHN when a strand of kelp anchored itself precisely over the gauge inlet. In 1992/93 the data were lost from one of the instruments due to a failure in the single-board computer that controls the operation of the gauge; this failure caused both the main and the RAM backup batteries to drain. Data recovery was complete from the other two gauges; fortunately these were the two that were closest to the May 1993 earthquakes.

Publications


Acknowledgements

Thank you to Kristine Larson and Mike Lisowski, who assisted with comparing the 1993 GPS data with the previous GPS and EDM measurements.
Figure 7. Complete data series from the three level lines with the longest histories. The improvement in data quality in 1980 coincided with some changes in our leveling technique, and casts a measure of doubt on interpretations of the pre-1980 data. The straight lines, slopes and statistics are from least-squares fits to the 1980-1992 data (as in Fig. 3).
References


Southern San Andreas Crustal Deformation

14-08-0001-G1809 - G-2315
Program Element II.3
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Investigations
1. Historical water level recordings from three sites around the Salton Sea are being investigated to determine tectonic tilting, taking account of as many noise and error sources as possible.
2. The tectonic tilt so derived is being compared with leveling data from the area.
3. LDGO-designed pressure-sensor gauges at five sites around the sea (Fig. 1) are being used to measure water level continuously, to investigate noise sources, to determine the level of detectability of tectonic tilt signals in the data, and to measure tectonic tilting.
4. A dense network of sites near the Southern San Andreas and northern Imperial Valley Faults (Fig. 1) is being surveyed approximately annually to cm-level horizontal accuracy, using Global Positioning System (GPS) techniques (in cooperation with Dr. R. Reilinger of MIT and others).

Results (January 1993)

Continuously-Recording Water Level Gauges and Leveling

The Data
We do not plot the original data from the pressure-sensor water level gauges since they are all basically similar, showing a ~40 cm annual cycle and a number of gaps due to vandalism, silting of the gauge site, and other problems (Beavan 1989). Only a small fraction of the gaps are due to data transmission link failures or to central computer problems; however, since such failures could be catastrophic, we installed solid-state backup recorders at the 3 operating remote sites in 1989. These have proved invaluable in recovering otherwise-lost data since that time. In January 1992, we also added a back-up recorder to the gauge at the SP central recording site.

A suite of differences between the observed water level series is plotted in Figure 2, after low-pass filtering at 4 day periods. These differences may be converted to apparent ground tilt (i.e., true ground tilt plus measurement noise of various sorts) by dividing by the distance between the gauges.

A long hiatus in difference series exists between mid 1990 and early 1992, with only the SB and FT gauges (on the west side of the Sea; see Fig. 1b) running more or less continuously through that time period. The problems, and our intended solutions, are described below.

Our site at BP went down in mid-1989 due to severe silting of the lake floor at its location. The landowner occasionally dredges near this site and we are hoping he will do this again soon. During a major field trip in February 1993 we will reinstall this gauge at its current site, or, if the dredging has not been done, at another location nearby.
Our site at BM succumbed in mid-1990 to rapid erosion of the north-eastern shore of the Sea. The pressure sensor is installed on an offshore post, and the recording electronics was installed in 1987 at a site some 20 m on shore. The shoreline eroded at an alarming rate and the site had to be temporarily abandoned when the electronics fell in the sea. In January 1992 the "cliff" marking the shoreline was only 1 m from the antenna mast; as of Dec 1992 the mast had also been washed away. The sensor is still in position, and we will reoccupy the site during our February 1993 field trip. This time the electronics will be installed even further on land!

The site at SP failed in mid 1990 and was eventually fixed in January 1992 by: (i) replacing the differential pressure sensor with two absolute sensors (one to measure underwater pressure and one to measure air pressure; and (ii) replacing the cable between the sensor housing and the on-shore electronics.

It was also necessary in January 1992 to completely reinstall the FT gauge. The gauge had been installed inside an onshore concrete cylinder belonging to Imperial Irrigation District
Figure 2. Differences between water level series after low-pass filtering at 4 day period. These differences may be converted to apparent ground tilt (i.e., true ground tilt plus measurement noise of various sorts) by dividing by the distance between the gauges. The rms value of these difference series is close to 1.0 cm. Positive trends on the plots indicate ground uplift of the second-named site relative to the first. Most trends are within the estimated noise level of ±3 mm/yr. Gaps are due to vandalism and other problems at one or both sites. (a) shows SB-SP water level differences since January 1986. SP apparently uplifted relative to SB at 3-4 mm/yr between Jan 1986 and early 1992 (i.e., down-to-south tilting). Our estimate of the error in this rate is about ±3 mm/yr - the error will decrease as the data length increases since the referencing of the gauge pressure datum to nearby benchmarks is a primary source of error, and is independent of data length. The dots below the data indicate times that a sensor was exchanged at one or other of the sites; since the trend continues through these changes we suspect it is not due to sensor instability. The triangles (filled=SB, open=SP) indicate times that staff gauges adjacent to the pressure sensors were read manually as a check on gauge stability; generally the agreement is 5 mm or better. The gauges have also been leveled annually to nearby arrays of benchmarks; their stability has been at the mm level. Leveling to more distant benchmarks also appears to indicate tilting down to the south-west (see text). During Fall 1989 there is an apparent change in the direction of tilting. We do not yet understand the source of this signal; strainmeters at Pifion Flat showed nothing unusual over the same time period.

(b), (c), (d) (overleaf). These plots show additional pairs of differences that include the other three gauges, BP, BM and FT. These gauges are also regularly checked for stability with staff readings and leveling; we have not, however, marked the plots as in Figure 2a. Note that SP also apparently uplifted at 5±3 mm/yr with respect to FT between 1987 and 1992.
Fig. 2 (b), (c), (d). See caption on previous page.
II

(IID) that was connected to the Sea via a pipe. IID were having trouble keeping the pipe unclogged and they eventually abandoned the cylinder. (The gap in the sb_ft signal in late 1991 (Fig. 2b) is due to the water level in the cylinder having become disconnected from the Sea.)

Figure 2b indicates that the sites SP, SB and FT were all running again as of January 1992, and the SB-SP difference is shown in more detail in Figure 2a. Despite the unexplained "reversal" in late 1989, the SB-SP difference shows a clear positive trend of 3-4 mm/yr (over 6 years), indicating relative ground uplift at SP (i.e., north up if thought of in terms of tilt). In Fig. 2a we plot times that sensors were changed at one or other of the sites (dots), and times that sensors were calibrated at each site by comparisons with manual readings of water level (triangles). The long-term SB-SP variations continue through these changes and calibrations without any obvious correlation, indicating to us: (i) that our calibrations are accurate, and that changes of sensor are carried out correctly without introducing biases; (ii) that the long-term signals are real (whether in the ground or in the Sea cannot be so readily decided).

The positive trend on SB-SP is corroborated to some extent by the negative trend on SP-FT (Fig. 2b), which also indicates relative ground uplift at SP, at a rate approaching 5 mm/yr over a 4 year period.

Explanations for water level signals: evidence from leveling

Can these observations be explained by a local instability (uplift) of the SP site? Local leveling from the SP gauge mount to nearby (~ 50 m) benchmarks indicates stability at the 2 mm level. Furthermore, leveling from NGS benchmark G70 (Fig. 1a), 0.4 km to the north, indicates steady subsidence of the SP gauge site relative to this mark (4.4±1 mm from Dec 1986 to Dec 1989; 4.6±1 mm from Dec 1989 to Jan 1992). This is in the wrong sense to account for the trend in the water level records.

One explanation for the SP to G70 leveling results is that G70 is unstable. This unfortunately cannot be ruled out as G70 is installed on a bridge abutment of the Southern Pacific Railroad. However, I would expect any instability of this mark to result in it settling downwards, which is in the opposite sense to the leveling results.

Uplift of SAF fault zone?

We are left with the possibility that the leveling and the water level results may both be indicating a real signal - uplift of G70 with respect to SP, and of SP with respect to FT and SB.

Such a signal is corroborated by leveling results of Sylvester (1991) further south across Durmid Hill (Fig. 3), and by a GPS reoccupation of Sylvester's level line by Bilham. Sylvester et al. (1992) have interpreted these measurements, along with geological observations, as indicating uplift of the SAF fault zone at Durmid Hill, and it is possible that we are seeing the same effect some 15 km north of Bilham's site.

As a partial test of this interpretation of our data, we also releveled from NGS benchmark V1255 to the local benchmark array at sea level site BP (see Fig. 1b). Only a single run of this 0.7 km level line was possible in the time available in January 1992, but this indicated a subsidence of the most stable of the local benchmarks relative to V1255 by 5.3±1.5 mm between October 1987 and January 1992.

This is in the correct sense to corroborate the other leveling results, but we caution against accepting it wholeheartedly until we double-run the line, and also occupy an
intermediate benchmark (halfway between V1255 and BP) that was missed during January 1992. We will also relevel the 0.4 km line between K1299 and BM (Fig. 1b), that was previously run in November 1987 and December 1989 with no significant change. We expect to complete this leveling in February 1993.

Figure 3. Leveling results from Bat Cave Buttes (after Sylvester, 1991). Bench mark BC01 is in the vicinity of V1255, which is plotted on Figure 1b.

**GPS Results**

We do not discuss the GPS results in this report since a major reoccupation of the network is due to take place in February 1993. Following the 1993 measurements, we do not plan another reoccupation of the network until 1995. In the intervening time we will concentrate on analyzing the backlog of data and interpreting our results.

**References**


Objective: The primary purposes of this study are to resolve the slip rate and determine the timing of past earthquakes on the Wildomar fault near Temecula, southern California. These data will further our knowledge of how slip is disturbed in southern California and provide a better estimate of the future earthquake hazard of the rapidly expanding Elsinore Trough region.

Results: We excavated a 600 m long trench near Temecula to constrain the total width of Holocene faulting. Three aerial photograph lineaments suggested that faulting may be distributed. However, the only active strand that we recognized in the Wildomar fault zone is expressed as a 2-4 m wide zone of shearing in Holocene floodplain and channel deposits.

The margins of a well-defined sand channel were exposed in our initial trench. We then excavated a trench across the fault about 40 m to the northwest, well as two trenches parallel to the fault zone, one on each side. These trenches exposed both channel walls of an ancestral channel to Temecula Creek with a channel trench at a high angle to the fault. Further trenches exposed the northern channel margin into the fault, and we will now hand-excavate the remainder of the exposure to precisely resolve slip. We will also excavate the southern channel margin.

The northern channel margin is laterally displaced about 5 m, but slip has yet to be precisely determined. Both detrital charcoal and freshwater snail shells have been recovered from the channel sediments and $^{14}$C dates are pending. These data will resolve slip and the maximum age of the past one or two events. In combination with previous trench data near Murrieta, we will have much better constraints on the last Holocene slip history of this important strand of the northern Elsinore fault.
Investigations

1. Monitoring program. Creepmeters are operated on faults in California to complement creepmeter arrays operated by Kate Breckenridge, Menlo Park, and Ken Hudnut, Pasadena. Data from 16 locations are collected during visits scheduled 3-4 times each year. Two instruments operate south of the Loma Prieta aftershock zone, five are operated in the Parkfield region (2 utilizing USGS telemetry), two on the Eureka Peak fault south of Landers, and two on the southern San Andreas fault at Indio and Durmid Hill. Continuous operating creepmeters are also operated on the San Jacinto fault at Anza, and two on the Superstition Hills fault, together with two manual observing sites. One of the Superstition installations is a differential creepmeter \cite{Bilham1992}. Approximately 10 additional temporary sites have been operated during the last few years during afterslip investigations.

<table>
<thead>
<tr>
<th>Creepmeter</th>
<th>location</th>
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<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Ranch</td>
<td>Parkfield</td>
<td>15 cm caliper</td>
<td>10 m</td>
</tr>
<tr>
<td>Water Tank</td>
<td>Parkfield</td>
<td>15 cm caliper</td>
<td>18 m</td>
</tr>
<tr>
<td>South HW46</td>
<td>Parkfield</td>
<td>15 cm caliper</td>
<td>8 m</td>
</tr>
<tr>
<td>Claussen Ranch</td>
<td>Parkfield</td>
<td>10 cm LVDT</td>
<td>20 m</td>
</tr>
<tr>
<td>Varian</td>
<td>Parkfield</td>
<td>1 m magnetostrictive</td>
<td>20 m</td>
</tr>
<tr>
<td>Indio</td>
<td>southern San Andreas</td>
<td>15 cm caliper</td>
<td>18 m</td>
</tr>
<tr>
<td>Durmid Hill</td>
<td>southern San Andreas</td>
<td>15 cm caliper</td>
<td>8 m</td>
</tr>
<tr>
<td>Anza</td>
<td>San Jacinto fault</td>
<td>50 cm caliper</td>
<td>10 m</td>
</tr>
<tr>
<td>Site zero</td>
<td>Superstition Hills fault</td>
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<td>8 m</td>
</tr>
<tr>
<td>Site 1</td>
<td>Superstition Hills fault</td>
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<td>2*8 m</td>
</tr>
<tr>
<td>Site 2</td>
<td>Superstition Hills fault</td>
<td>15 cm caliper</td>
<td>8 m</td>
</tr>
<tr>
<td>Site 3</td>
<td>Superstition Hills fault</td>
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<td>8 m</td>
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<tr>
<td>Nyland Ranch</td>
<td>San Andreas San Juan Bautista</td>
<td>15 cm caliper</td>
<td>8 m</td>
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<td>San Andreas Pajaro River</td>
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<td>136 m</td>
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<td>12 m</td>
</tr>
<tr>
<td>Juarez Rd</td>
<td>Eureka Peak Fault (discontinued)</td>
<td>15 cm caliper</td>
<td>8 m</td>
</tr>
</tbody>
</table>

2. Improvements to creepmeters. Creepmeters installed in afterslip studies use a 15-cm-long digital caliper attached to a 1 cm diameter invar rod, 6-8 m long enclosed within a PVC tube installed horizontally 30 cm underground, and at 30 degrees oblique to the fault \cite{Bilham1989}. In extended monitoring programs where a narrow surface fault has not been revealed by recent rupture, 10 or more screw-together 2-m-long invar bars are used. Recently we have experimented with continuous lengths of glass-fiber coated with teflon. This material has similar thermal characteristics to Invar but is lighter, tougher, corrosion free, and comes in 300 m lengths.

The Tandy 100 computers that performed all the data logging of our earlier systems are no longer available and we have replaced these with ATARI IBM-compatible palmtop systems that fit into a 10 cm diameter, 25 cm long watertight cylindrical tube. The computers have up to 500 k
of memory and can record if necessary at rates up to 1 sample per second. Our preferred sample rate is 1 sample per minute for creep events (detected automatically by a fault slip velocity greater than 0.05 mm/hour) and one sample per hour at other times. The digital caliper systems are also installed in watertight compartments and communicate with the computers using integral RS232 optoisolators. We have discontinued the measurement of temperature because the instruments are essentially immune to typical surface thermal signals at their operating depth and recording sensitivity of 10 μm.

With Kate Breckenridge of USGS we are experimenting with a new type of sensor based on a magnetostrictive sensor with ranges of 15 cm to 100 cm. A pulse is delivered to a magnetostrictive wire whose two way travel time is determined by sensing electronics to 16 bit precision (e.g. 15 μm for a 100 cm range device). The two way travel time is determined by the a magnet attached to the end of the creepmeter rod, that slides on the outside of the sealed tube supporting the magnetostrictive wire. The output is either frequency or voltage providing both high resolution and large range with a sampling rate >100 Hz. A pilot instrument has been installed at Varian where its dynamic range permits it to measure both the Parkfield coseismic signal in addition to regular creep events.

![Figure 1](image_url)  
**Figure 1** Afterslip on the Superstition Hills fault. The decay approximates a semi-logarithmic curve that prior to the Landers sequence was contained entirely within the shaded region. Vertical steps represent creep events. Creep occurs on the fault between creep events at rates of less than 10 μm/day.

**Results**

1. **Superstition Hills and San Andreas fault slip triggered by the Landers sequence.** The Superstition Hills Fault in the past several years has slipped in large creep events (≈1 cm) that have occurred recently approximately once per year (Figure 1). Each creep event contains 3 or more sub-events and 80% of the slip is complete within a few hours. The long-period rate of decay of slip on the Superstition Hills fault has been determined by *Wennerberg and Sharp* (1-D Dynamic modeling of post-seismic strain release, Eos. Trans Am. Geophys. Un., 74, 195, 1993) to obey a modified form of the decay curve proposed by *Marone et al.* (1991). The 1992 creep event was followed within 6 weeks by a creep event triggered by the Landers earthquake, which also triggered slip on the southern San Andreas fault [*Bilham et al. 1992; Bodin et al. 1993*]. Although the slip triggered on the Superstition Hills fault did not exceed that expected from the long-period afterslip decay rate, an anticipated late 1993 creep event is evidently overdue (Figure 1).
Triggered slip also occurred on the southern San Andreas fault at Indio and Durmid Hill. The slip velocities and timing of these triggered slip events indicate that slip was initiated in the first minute of the Landers mainshock reaching peak velocities of 2.5-3 mm/minute, within 2 minutes of the mainshock on the southern San Andreas fault, and 4.2 mm/minute on the Superstition Hills fault within 3 minutes of the mainshock (Figure 2 and 3). Minor triggered slip accompanied the Joshua tree and Big Bear mainshocks at some of the sites [Bodin et al. 1993]. It would appear that the triggering mechanism may be related to the depth and intensity of surface waves crossing a creeping fault, and may be related to transient increased pore pressures. The amplitudes of these waves are amplified by the sedimentary setting of the subject faults, and triggering appears to be confined to transpressive parts of the San Andreas fault where surface seeps are common and where pore pressures are presumably higher than in intervening fault segments.

Fig. 2 Details of triggered slip displacement and velocity on the Superstition Hills Fault

Figure 2 Triggered slip and velocities on the Southern San Andreas fault for the Landers sequence

2. Post Landers mainshock afterslip on the Eureka Peak Fault  Five locations were instrumented with creepmeters starting the day after the Landers' mainshock. No significant afterslip occurred on the main fault trace north of the Pinto Mountain fault although 1-3 mm of slip was recorded at most of the instrumented sites presumably related to settling following installations. In contrast, three additional creepmeters recorded afterslip on the Eureka Peak Fault in the suburbs of Yucca Valley [Behr et al., 1993]. Approximately 8 cm of dextral slip has occurred at San Andreas Road since one week after the Landers mainshock, and creep continues at a low rate (<1 cm/year). An additional 1-3 cm may be expected based on the current decay rate, bringing total surface slip into approximate agreement with the 25 cm of slip inferred to have occurred on the fault at depth. Creep on the northernmost of these sites occurs as a decaying
afterslip rate upon which rate changes are superimposed that correspond further south with episodic creep events. We surmise that episodic creep may not be possible near the northern end of the Eureka Peak fault either because the sedimentary cover here is shallow, or because the fault is terminates not far to the north, or because a gouge zone may be absent due to the shortness of the length of the fault, or to the youthfulness of its northern end which may represent an incipient propagating fracture.

3. Rain and strain at San Juan Bautista - a precipitated slow event in Dec 1992?
Cumulative slip at Nyland Ranch since the 1989 Loma Prieta earthquake exceeds 6.5 cm [Behr et al. 1993], which, though established by a post Loma Prieta rate-increase 3 times the preceding two-decade average, represents a negligible fraction of the >4 m of slip overdue on this segment of the fault inferred to have developed in the past century [Bodin and Bilham, 1993b]. The absence of slip here is apparently real because an alignment array indicates a narrow fault zone spanned adequately by the creepmeter. Curiously, a deep creep event inferred by Johnson et al. 1993 and Gladwin et al. 1993 (Eos. Trans Am. Geophys. Un. Fall Meeting abs 1993) to have released slip equivalent to an M5 earthquake directly beneath the creepmeter, was not manifest simultaneously as surface creep (Figure 3). The December 1992 event, which because of its uniqueness in size since strainmeter installation is described as a slow earthquake, may have released as much as 10 cm of slip, however, in the following year less than 1.5 cm of slip has been manifest on the surface fault at Nyland which lies above the inferred slip zone. A slight increase in rate, however, was recorded by the creepmeters superimposed on the Loma Prieta afterslip decay curve, equivalent to 8 mm of additional slip at Nyland above the 7 mm expected from post Loma Prieta decay rates. It is possible that the deep creep event is associated with less than 3.5 mm of simultaneous surface slip perhaps because 6.5 cm of surface slip has already occurred here since the Loma Prieta event. To this must be added the accumulated surface slip of approximately 7 cm/decade from at least 2 previous decades. This would suggest that similar slow earthquakes could occur at decadal intervals.

However, a disturbing aspect of the inferred slow earthquake, noted by Kate Breckenridge, is that it occurred during the time of the heaviest rainfall in the region since the Loma Prieta earthquake (Figure 5). The Nyland creepmeter is installed in clays which tend to flood in times of heavy rain, the reason for its abandonment as a viable creep monitoring site by the USGS many years ago. Each downpour causes the clays to swell in a few hours, causing apparent left and right lateral signals which recover over periods of days. Both the dilatometer and the Nyland creepmeter record incremental rate increases at events numbered 1, 2, 3, 6 and 7 in Figure 3.
although some of these correlations are not clear on this small scale plot. These signals are not uncommon on the Nyland creep data, yet are unique in the strain data. No heavy rain occurs at event 4 or event 5 in the creep and strain data, although we note that the rain gage is several km from each of the instruments. The conclusion that the slow event was "precipitated" in some way by rain appears unavoidable, yet the triggering mechanism must require contributions from other physical variables because rain is an annual event and accompanying large strain dilatations are confined to this single event. Its dismissal as an instrumental artifact or, for example, as rainwater filling a vertical tabular crack near the dilatometer borehole) can be excluded because of temporal correlations with a nearby shear-strainmeter not shown here, because shallow seismicity accompanied the events, and because the 1 μstrain strain increase has not recovered. The net surface creep at Nyland and nearby xsj2 is similar for the month of December.

4. San Jacinto fault at Anza

No creep events have occurred at this site since installation in January 1990. The data show irregular expansion and contraction of less than 0.3 mm/year across the fault. No triggered slip occurred here at the time of the Landers’ sequence.

5. San Andreas fault at Parkfield

A new 20 m long creepmeter has been installed in thick fault gauge at Claussen Ranch on Middle Mountain at the northernmost location where afterslip was recorded in 1966. The instrument is a collaborative venture with the USGS and data are telemetered via satellite to the low frequency data base. The creepmeter uses a 10 cm range LVDT and a 1 cm diameter glass-fiber length standard to cross the fault which at this location runs through a gully on a hillside. The 1 m dip in the creepmeter results in stick-slip behavior with 10-60 μm amplitude. Since September 1993 a creep rate of 0.8 mm/month has been observed. The M5.3 A-level alert event beneath Middle Mountain in mid-November triggered 0.3 mm of slip at this site.
Reports


Mammoth Lakes Biaxial Tiltmeter

Grant 1434-92-G-2191
Program Element II.4
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Investigations

1. A biaxial tiltmeter is maintained at Mammoth Lakes as part of the alert system for possible volcanic eruptions in the Long Valley, Caldera and as a direct monitor of inflation of the subsurface magma chamber. Egill Hauksson of Caltech operates a Terrascope station in the southernmost of the three underground vaults that provides access to the tiltmeter.

Operating parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>37°37'58&quot;N, 118°50'01&quot; West (center vault)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East/West tiltmeter</td>
<td>length 423.3 m azimuth 280° precision 0.57 nanorad</td>
</tr>
<tr>
<td>North/South tiltmeter</td>
<td>length 449.2 m azimuth 16° precision 0.53 nanorad</td>
</tr>
<tr>
<td>Remote range</td>
<td>±20 μrad (100 db), manual adjustment to ±200 μrad</td>
</tr>
<tr>
<td>Pipe</td>
<td>20 cm diameter PVC at a mean subsurface depth of 1.5 m.</td>
</tr>
<tr>
<td>Vaults</td>
<td>Three 2.7 cm diameter corrugated-steel. Mean floor depth 2.5 m.</td>
</tr>
<tr>
<td>Vertical extensometers</td>
<td>LVDT Sensors coupled to the ends of 6 mm diameter Invar rods held in tension. Lengths ~20 m. sensitivity 0.5 μm, range 6 mm</td>
</tr>
<tr>
<td>Water level monitors</td>
<td>1. Four equal-arm Michelson-Interferometers powered by polarized He/Ne lasers. Resolution 0.25 μm, range 1 cm.</td>
</tr>
<tr>
<td></td>
<td>2. Four CCD displacement sensors. Range 10 cm resolution 1 μm</td>
</tr>
<tr>
<td></td>
<td>3. Two float sensors Range 1 cm resolution 1 μm</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>18 minutes underdamped</td>
</tr>
</tbody>
</table>

Results

1. Continued inflation. Data from the interferometer transducers since the onset of 1989 inflation are presented in Figure 1 as edited and smoothed data from which tides are removed. The data show a general tilt to the ESE corresponding to the inflation of a magma chamber at a mean rate of approximately 1.9±0.1 μrad/yr. Data prior to 1989 show no significant tilt. Minor tilt rate changes occur at times of increased microseismicity in Long Valley and Behr (1992) has correlated these tilt fluctuations with inflation episodes in different inferred magma chambers and active faults in the region. These correlations depend on data from the two-color geodimeter without which the location of the magma chamber would be an unknown in the interpretation of the tilt vector. With one additional tiltmeter with the sensitivity of the present unit it would be possible to determine the location, depth and inflation rate of the magma chamber independently of other methods.
An end-of-range condition occurred during spring thaw conditions in 1993 caused by uplift of the central vault. The counterbalance system that holds the vertical invar rod in tension reached the end of its range, thus for approximately 1 month the shared vault was without a vertical reference to the 20 m base of the borehole. The error has been corrected with a larger range LVDT in order that future vertical displacements may be monitored more reliably. The vertical correction signal has been estimated from the 1.6 mm of uplift recorded by the vertical reference system prior reaching the end of its range, supplemented by the vertical signal coherent between the east and north water height transducers. The 1993 data compliment the geodimeter data in that they indicate continued inflation of an inferred magma chamber. The rate remains similar to the mean 1989-1992 rate of 1.9 μrad/year.

Using 1989-92 GPS data from Dixon et al. (1993) and the Michelson tilt vector data up to 1992 we find that the data are consistent with the inflation of a point source magma chamber at 9 km depth inflating at a rate of 0.008 km³/yr (Figure 3), a magma supply rate of ≈250 litres/sec. These values are in approximate agreement with magma chamber inflation rates and depths inferred from the two color geodimeter data from the caldera (Langbein et al. 1993). An annual thermoelastic signal of approximately 250 nrad modulates the surface tilt vector in Figures 1 and 2.
2. Tilt at Mammoth Lakes following the 28 June 1992 Landers earthquake. Microseismicity started occurring soon after the Landers mainshock of 28 June 1992. A short period perturbation to the tilt signal also occurred at this time (Fig. 4). The tilt signal may be viewed as a tilt away from the inferred magma chamber with an amplitude of 0.2 μrad and a duration of 7 days that recovers in the following 2 weeks. A tilt vector plot illustrates this transient tilt. Mogi-type models would require the temporary injection of a volume of magma equal to a sphere of radius 58 m at a depth of 9 km (or one of 45 m radius at a depth of 7 km) at the location of the magma chamber discussed in Figure 3. This is approximately a one month supply of magma at the mean 1989-92 rate, and although the injection rate would have to be roughly 5 times faster it is similar to the late 1993 rate.

3. New sensors. We are currently re-processing the Mammoth data using data from the Michelson interferometers and optical charge-coupled devices. We anticipate revised estimates for the current inflation rates when this is completed.

Reports
Deep Reference Monuments for Precise Geodesy in Unstable Surface Materials

Grant 1434-93-G-2300
Program Element II.3
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Investigations

It is of importance that the stability of the control points used in crustal deformation programs is superior to the accuracy of the measurements used to determine their relative positions, yet this is not always possible. Occasionally weak sedimentary rocks or water saturated soils are the only materials available for hosting control points. Examples in the US are parts of the LA Basin and San Francisco Bay, and the New Madrid seismic zone, and regions such as the Gangetic Plain and the weak alluvial slopes of the hills fronting the Himalaya in India.

The project evaluates a method to relate surface measurements to presumed more stable subsurface layers at depth using a borehole inclinometer system. Tilt measurements made incrementally along a prepared borehole provide a measure of offset at each depth which are integrated to determine the offset of the surface relative to the base of the hole.

A test borehole was drilled in steeply dipping shales in a relatively stable region near Boulder, Colorado to quantify systematic and random errors in the measurements. A grooved lining 70-mm in diameter was inserted to a depth of 30 m and backfilled with concrete and bentonite mix to ensure good coupling to the host rocks. A Mk 4 Geotechnical Instruments inclinometer was used for the measurements. The instrument consists of an orthogonal pair of force feedback accelerometers with a range of ±7 degrees and a precision of 10 μrad.

Results

1. Random errors. The 50-cm-long probe is guided by self-centering wheels that permit the lateral deviation of the hole at each 0.5 m depth to be measured to 5 μm precision, and in the absence of other sources of error the cumulative random error would grow with depth as the square root of the number of measurements. For example in a 30 m deep hole with 60 setup the theoretical error is 40 μm. Uncertainties in the zero offset between the mechanical zero of the probe and the electronic zero of the tiltmeter are removed.
by making measurements using the inclinometer in opposing directions at each depth. This provides both an “absolute” inclination, free from the zero datum drift encountered in fixed tiltmeters, and a realistic measure of the “noise” in the measurements.

The scatter in the mean value of the data at different depths was obtained by undertaking numerous measurements of the entire borehole over a period of a few months. The experiment then examined the RMS deviation at each of 60 set-ups down to the 30 m hole. The RMS deviations at 10-30 m depth were found to be systematically lower (0.030 mm) than those in the uppermost 10 m (0.048 mm) suggesting that the measurements near the surface include real movements of the borehole lining (Figure 2). If the mean of the lower deviations are used to project the growth of random error, error grows according to \( \sigma_r = 0.03 \sqrt{N} \) mm (Figure 3) where \( N \) is the number of set-ups down hole (\( N=\)twice the depth in m). In order to appreciate the accuracy of the measurement in terms of other forms of geodesy it is of value to express the error growth in terms of the depth of the borehole in km, \( L \), thus \( \sigma_r = 1.34 \sqrt{L} \) mm which may be recognized by its similarity to the growth of random errors in First Order, Class-II leveling. By reducing the number of set-ups per m of hole depth it is theoretically possible to match the accuracy of Class-I leveling. For example, were the body of the inclinometer to be increased to 2 m the growth of error with depth would be 0.7\( \sqrt{L} \) mm.

2. Systematic errors. Although there is no datum drift in the measurements because opposing measurements of inclination at each depth are averaged, any change in calibration will cause an inclined borehole to increase or decrease in apparent inclination. The dual-axis inclinometer system used in this study boasts a tilimeter linearity of 0.02% of full scale (30°). Thus, assuming that the calibration of the accelerometer is true to within 0.02% over the entire range, and that the cumulative error in the measurement is not biased by slope-dependent errors over parts of the range, the resulting lateral error, \( e_s \), is proportional to the net lateral offset between the base of the hole and the top of the hole. This is similar in character to height-dependent errors in spirit leveling. Thus \( e_s = k(e) \) mm where \( e \) is lateral offset in m between base of hole and surface and where \( k \) is the calibration accuracy expressed as a percentage of fullscale.

For the 30-m-deep Table Mountain borehole (Figure 1) a 0.02% calibration error causes a 0.09 mm error in the NS direction (top-to-bottom offset 47 cm) and a 0.02 mm error in the E/W direction (offset 11 cm). In contrast the random error for each set of 60 measurements is 0.24 mm. In accord with these formal errors the repeatability of a pair of measurements made within a few hours of each other is observed to be <0.5 mm. Note that there is no calibration
error in a vertical hole, which points to an important installation criterion. In practice, vertical
holes are difficult to obtain and holes (of any depth) within 5 m of vertical should yield
accuracies better than 1 mm given the quoted calibration accuracy.

3. Blunders. That the RMS error of 0.03 mm is merely 3 times worse than the precision of
the measurements is an indication that the cumulative errors from wheel roughness, bearing
roughness, and lining smoothness effectively contribute less than 30 \( \mu \)m to “set-up” error.
The data from an orthogonal accelerometer inside the probe is used by a built-in
microprocessor to correct cross-coupling errors in the primary tilt axis calibration. However,
the growth of random errors in the cross axis measurement depends on the “tightness” of
the walls of each groove. Perhaps because of this, the repeatability in the orthogonal axis is
determined to be typically twice as bad as that in the primary axis.

A problem arises if a piece of dirt lodges under one of the leading wheels at a point of
measurement that is not encountered by the trailing wheel at the next contiguous
measurement, or on the following measurement run with the inclinometer reversed. This is
not fatal because the two pairs of measurements made at each depth result in two checksums
that should be reproduced throughout the hole. A transient blemish in the groove will
change radically the checksum (automatically displayed by the data logger at the moment of
measurement) and the measurement can be repeated. If the error is not detected in the field
this form of blunder appears as an outlier in one of the readings and may typically removed
in subsequent processing. If the measurement at a specific depth is inadvertently entered into
the data logger before it has settled to its final value (6 seconds is usually required) the data
are not possible to correct and the measurement at this depth must be removed in subsequent
analysis. Fortunately this is a measurement blunder that occurs infrequently, although an
experimental modification is being considered that would acquire the data automatically 10 s
after the inclinometer is placed at each depth.

The azimuth of the borehole lining spirals by less than 1° per 10 m. For deep boreholes a
spiral gauge is available that determines the rotation of the spiral with depth. The ABS lining
is unsuitable for use in environments where elevated temperatures exist. Thus deep holes
would need to use a stainless steel lining.

4. Applications. Borehole inclinometry evidently offers a precise method to transfer lateral
positions from subsurface points to the surface and to examine the increase in effective
stability with depth. A sub-mm horizontal control accuracy is easily obtainable from a 30 m
borehole, and 2 mm accuracy is theoretically obtainable from a 2-km-deep borehole. The
borehole inclinometer approach can replace or supplement methods that attempt to obtain
lateral surface stability using rods driven to refusal or deep piers. The cost of the borehole
lining is approximately $15/m and can be inserted wherever a vertical borehole is available,
even as a temporary (sprung supported) or permanent (concrete grout) retrofit to an existing
borehole.

The increase of lateral stability with depth can be quantified both from the reduction in
variance with depth where frequent measurements are obtained, and from the reduction in the
change in the amplitude of deviation of the hole with depth. Although these measurements by
themselves do not include translation information they typically reveal the long-term and
short term components of borehole flexure, that is the vertical velocity field.

5. Subsurface geodesy. The similarity between the errors encountered in First-Order leveling
and borehole inclinometry suggests the possible development of deep subsurface geodetic
measurements to complement surface investigations. The depths of exploration are limited to
a few km although 5 km holes might be used in areas of special importance (e.g. LA Basin
buried thrust faults). Note that at 5 km depths lateral uncertainties are 3 mm with existing borehole technology, similar to those encountered in GPS and trilateration over surface distances. With simple design modifications it appears possible to reduce these uncertainties by more than a factor of 2 rendering the measurement of lateral subsurface position more accurate than surface geodesy. An attractive feature of inclinometer holes is that they may be used by triaxial seismometers or biaxial tiltmeters between measurements.

An important application of borehole inclinometry is perceived to be the investigation of creep on parts of the San Andreas system where boreholes may be drilled to depths where these processes are operative.

Reports

Creepmeters on the Hayward Fault

Grant 1434-93-G-2308

Program Element II.3

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Investigations

The long term slip rate responsible for earthquakes on the Hayward fault is 7-9 mm/year. Alignment arrays indicate that the surface fault slips at rates of 5-9 mm/year suggesting that surface creep releases much of the elastic strain that would otherwise be released by earthquakes on the fault. Slip at depths greater than 7 km occurs seismically but its relation to shallow aseismic slip is obscure. The objective of the measurement program is to install telemetered creepmeters at approximately 10 km intervals along the fault to provide a continuous monitor of fault slip, and to learn more about the relation between deep seismicity and shallow slip. The telemetered data are of potential utility to BART, whose trains cross the fault every several minutes. The probability for the fault to slip just before a train passes is high.

The creepmeter installations encounter two problems: annual displacements are similar in amplitude to near-surface noise in soils caused by variations in moisture content and temperature, and the installations must be undertaken in an urban environment of subsurface utility networks and private and publicly owned rights of way.

Results

In collaboration with Kate Breckenridge and Jim Lienkamper and guided by the fault-crossing measurements of Jon Galehouse we have identified a half-dozen potential locations on the Hayward fault and have proceeded to secure permission to drill and excavate trenches for creepmeter installation. Permission has been granted for two sites of which one has been completed. The site is the abandoned Gallegos winery on Osgood Street, Fremont, where we were able to determine the location and long term slip rate of the fault to within a few meters from an offset foundation installed in the late 19th century.

The Gallegos installation consists of two 25 cm diameter, 30 m deep vertical cylindrical pillars 25 m apart on either side at an angle of 30° to the fault. The pillars are reinforced to a depth of 7 m and are equipped with an inclinometer lining to monitor their long-term tilt and flexure to an accuracy of ±0.25 mm. A teflon-coated, glass-fiber length standard is buried at a depth of 1 m within a PVC lining and fastened directly to the NW pillar. Two Linear Variable Differential Transformers monitor the free end relative to the SE pillar with an accuracy of 1 μm over a range of 10 cm. The data are transmitted to Menlo Park every 10 minutes using a 12 bit Sutron DCP.

Relative motion between the two pillars induced by heavy rain within a few weeks of installation has been less than 0.5 mm although these motions may be unrepresentative of longer term behavior. Cumulative artifacts of pier tilt greater than 0.5 mm will be suppressed using inclinometer measurements at intervals throughout the year.

Reports

A Strategy for Obtaining High Spatial and Temporal Resolution of Crustal Deformation using GPS

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USGS 1434-92-G2196

Program Element II.3: Determine the Nature and Rates of Crustal Deformation

Objectives

GPS surveying has the potential to provide crustal deformation precursors for the prediction of large earthquakes and, in particular, to allow frequent and dense monitoring of interseismic, coseismic and postseismic strain transients which would add to our fundamental understanding of the physics of the earthquake process. The goal of this research is to develop and evaluate the capability of surveying spatially dense, local to regional scale, three-dimensional geodetic networks, in near real-time with several millimeter-level accuracy using GPS in continuously operating and kinematic-type modes.

Investigations Undertaken and Data Collected

The Permanent GPS Geodetic Array (PGGA) has been operated in southern California since the spring of 1990 by SIO and JPL with assistance from MIT, UCLA, Caltech and USGS (Pasadena Office). Funding for the operations and analysis of the network is provided by SCEC, NASA, NSF and USGS. The goals of the PGGA are to monitor crustal deformation related to the earthquake cycle in California, continuously, in near real-time and with millimeter accuracy. The PGGA also provides reference sites to support detailed GPS geophysical surveys in southern California. The Landers earthquake sequence generated the first real geophysical signals that were detected by PGGA. Data collected around the period of the Landers and Big Bear earthquakes have been studied extensively for coseismic and postseismic deformation. PGGA data have been a very important asset for our investigations of the spatial and temporal resolution of GPS under this award.

We have developed an automated system to collect, analyze and archive data from the PGGA sites and from a globally distributed set of about 30 GPS tracking stations of the International GPS Service for Geodynamics (IGS) (Figure 1). We monitor data at a 30 second sampling rate to all visible satellites, 24 hours a day, 7 days a week.

Results Obtained

We have been estimating the position of the PGGA stations daily since August 1991. We perform, at twenty-four hour intervals, a simultaneous weighted least squares adjustment of the station positions and improved satellites ephemerides. During this period, we have also been generating precise satellite ephemerides and improved earth orientation parameters (polar motion) in support of GPS surveys in southern California. These products are available via anonymous ftp over Internet within 5-7 days of collection. We evaluate the precision of our satellite parameters based on overlapping orbital arcs and baseline repeatability. Our orbital ephemerides are sufficiently precise to support any crustal deformation GPS survey in California, thereby eliminating the time consuming and
costly need for each investigator and/or analysis center to compute their own orbit improvements. Since the coordinates of the PGGA sites are computed with respect to the International Terrestrial Reference Frame (ITRF), realized through the positions and velocities of the global IGS stations, crustal motion can be determined in a reference frame external to California.

The ability to determine "absolute" positions in southern California, rather than baseline positions between pairs of stations, was invaluable during the Landers earthquake [Bock et al., 1993]. We were able to determine coseismic and postseismic displacements at each site with respect to the ITRF reference frame. Therefore, we were able to make direct comparisons with site displacements computed from elastic half-space dislocation models of the earthquake. In order to improve the "absolute" positions we developed a filtering technique that removed systematic errors that were common to all of the PGGA sites on a day-by-day basis [Bock et al., 1994]. As an example, we show in Figure 2 the raw unfiltered time series of the positions for the site at Pitzer Flat Observatory (PIN1) and in Figure 3 the filtered time series. There is a significant improvement in the filtered series in the determination of interseismic deformation and coseismic displacements. In Figure 4, we focus on the 10 week period centered on the day of the Landers earthquake. After filtering we can distinguish a post-seismic signature at PIN1 of about 1 mm/day for the two week period following the earthquake [Wdowinski et al., 1994].

We have computed (in collaboration with Ken Hudnut) significant compression across the Los Angeles Basin from only several months of data from the PGGA sites at Lake Mathews (MATH) and Palos Verdes (PVEP). We compute 5.5 mm/yr of compression which compares well with earlier estimates obtained from several years of periodic occupations with VLBI and GPS [Feigl et al., 1993].

We have tested distributed processing schemes for the PGGA and IGS analysis since the numbers of global and PGGA stations are increasing steadily. Since the time required for data editing increases by a factor greater than the number of stations, and the time required to invert the normal equations by approximately the cube, processing of two smaller networks is more efficient than one large one. To test the feasibility of this concept, we re-analyzed the 70 days of observations from 1992 used to determine coseismic displacements from the Landers earthquake. One network consisted of the global network (26 stations) plus two PGGA stations (DS10 and JPL1), the other the 5 PGGA stations operating at that time (including DS10 and JPL1). We then combined the (2 x 70) solution files from the separate analyses using the GLOBK software package. The coseismic displacements estimated from this analysis were statistically equivalent to those obtained using simultaneous processing (Figure 5).

We have tested the feasibility of near real-time processing. In Figure 6 we show the time series of station positions for the 91-km baseline between the PGGA sites at Lake Mathews and Palos Verdes, computed using SIO orbits that have been extrapolated for 24 hours. There is no significant degradation in the repeatability (2-4 mm in the horizontal and 20 mm in the vertical) compared to using orbits estimated from the same day's data (there is significant degradation when extrapolating the orbits 48 hours). This example implies that we could compute useful orbits in almost real-time (except for anomalous maneuvers of the satellites) if data from the global tracking network could be available within 24 hours. This example also shows the type of precision that can be expected by users of the PGGA system in southern California for 24-hour site occupations.
Reports published (1993)

Journal articles


Conference Proceedings


Abstracts


Figure 1: The current distribution of the tracking stations of the International GPS Service for Geodynamics and the PGGA sites in southern California.
Filtered Time Series of Positions for Station PIN1 (mm)

Figure 3
PIN1 - North - Unfiltered

PIN1 - North - Filtered

day number, 1992

Figure 4
Figure 5. Observed (solid arrows) and modeled (blank arrows) displacements at four of the PGGA stations in southern California due to the Landers and Big Bear earthquakes of 28 June 1992. We show the displacements and 95% confidence ellipses computed processing the PGGA and IGS data in a simultaneous global solution (unshaded ellipses) and using the distributed processing approach explained in the text (shaded ellipses). The observed displacements are with respect to a global reference frame and, therefore, indicate absolute displacements of the California sites. The contours of displacement magnitude and the computed displacements are based on an elastic halfspace assumption for the behavior of the Earth's crust (all units mm). The surface trace of the Landers rupture is indicated by a heavy line and for the Big Bear earthquake by a dashed line.
Figure 6. Time series for daily baseline determinations between the PGGA sites at Lake Mathews (MATH) and Palos Verdes (PVEP), in terms of north, east, and vertical components and length. Each point represents a solution based on 24 hours of data.
Slip Rates in the San Francisco Bay Area

1434-93-G-2356
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Investigations Undertaken:
In 1993 we continued our investigations with kinematic models of faulting in central California. Moreover, we began to apply 3-dimensional boundary-element models to study the scaling of slip with rupture length. Our investigations follow 4 themes:

1. We find that mean geological slip rates on fault segments in California are related to the length of the fault zones of which they are part. The slip rate is not, however, constant along a fault zone, but varies along strike. We can estimate the “connectivity” between fault segments and fault zones from slip rates observed paleoseismically, measured directly along creeping segments, and from the historic seismic record. Once the fault connectivity has been established, our models permit us to estimate the slip rates of all faults within the plate boundary.

2. Combining the fault connectivities with the historic record of fault slip, we can assay the slip deficit along a fault zone. Thus, using the best currently available record of historic fault rupture in the San Francisco Bay area together with our preferred models of slip rate along the San Andreas Fault in central California, we sought to answer two questions: 1) Did the 1989 M7 Loma Prieta earthquake occur in a region of previously-recognizable slip deficit? 2) Has it completely relieved the slip-deficit where it occurred?

3. We have also used our models to estimate the effect of the Loma Prieta earthquake on the state of strain surrounding nearby faults, and tested those models by examining changes in surface creep rates on nearby faults.

4. We have explored the consequences of the pattern of plate-boundary strain accumulation measured geodetically for the scaling of slip with rupture length for earthquakes within the plate boundary.

Results:
1. Fault zone length is an important factor in determining slip rate: fault segment connectivity and applied strain rate are of equal importance in determining long term slip rates. Slip rates vary along the strike of a discontinuous fault zone, and may be significantly modified by interactions with neighboring fault zones. It is thus inappropriate to apply point estimates of slip rate to entire fault zones as is now common practice. Best agreement between model results and observed slip rate data is obtained in a model in which the Rodgers Creek, Hayward and Calaveras faults are connected along strike, and the Maacama fault slips in isolation. An extended Mission Fault is invoked to link the Hayward and Calaveras faults. Elsewhere we include short hypothetical fault segments corresponding to regions of diffuse seismicity, to connect fault zones. We find that the slip rates on all of the East Bay fault zones (Fig. 1) are sensitive to the length of the Maacama fault, which is estimated to be between 110 and 160 km. In models in which the Maacama fault is locked, the mean slip rate on the Hayward fault does not exceed 5 mm/year. We find that the observed variation in slip rate on fault segments in the San Francisco Bay Area of California is consistent with connectivity between the Hayward, Calaveras and San Andreas fault zones. Slip rates on the southern Hayward fault taper northward from a maximum of more than 10 millimeters/year and are sensitive to the active length of the Maacama fault.
2. Our models suggest that the difference between the cumulative slip attributable to historical ruptures and the slip estimated from plate-tectonic motion in the San Francisco Bay region exceeds 1 m and in some places is as high as 3.5 m (Fig. 2). Regions to the northwest and southeast of the Loma Prieta rupture zone currently exhibit the largest slip deficit, which may be sufficient to drive future m~6.5 earthquakes.

3. Were the San Andreas and Calaveras faults frictionless, vertical dislocations, more than 20 cm of surface slip would be induced on the northernmost 20 km of the creeping section in response to strain changes accompanying the Loma Prieta event. Induced additional post-seismic surface slip nowhere exceeds 4 cm, indicating that much of the potential fault displacement in the northern creeping section has not occurred. While post-seismic displacements up to September 1992 have attained only 10 to 20% of modelled values, the spatial distribution of post-seismic surface slip rate increases reflects the results of these simple models (Fig. 3). In particular, potential slip and creep rates are predicted to be much reduced south of the San Andreas' intersection with the Calaveras fault.

4. Shear strain within a transform plate boundary is manifest geodetically as a velocity field with a sigmoidal surface profile that approximates an arctangent function. Although elastic strain may extend to great distances from the plate boundary, more than 90% of relative plate displacement is manifest within a narrow region near the center of this velocity field. In California, for example, the breadth of this region varies from less than 50 km to more than 120 km, broader fields being associated with activity on several parallel fault zones. The narrowness of the velocity field imposes important constraints on the displacements on fault surfaces during earthquake rupture (Fig. 4). We find that for small earthquake ruptures mean slip is proportional to the strain at failure, whereas for ruptures long compared to the breadth of the velocity field, mean slip is limited by the plate displacement developed since the last great earthquake(Fig 5). The transition in behaviour occurs for earthquakes (M~7) that just fill the seismogenic width of the transform boundary, accounting for the well-known observation that large earthquakes obey different scaling laws from small earthquakes. Our model explains several aspects of plate-boundary seismicity, including why moderate ruptures initiate at depth, why seismicity rates are low remote from the ends of large ruptures during the interseismic stage of the earthquake cycle, and why ruptures of some moderate earthquakes may not break the surface (Fig. 6).
Fig. 1 Slip rates on the Hayward and Calaveras fault zones estimated using our preferred fault connectivity. Observed values for slip are indicated by vertical lines and by a cross. The upper limits of the outlined areas are fault slip rates anticipated from a 151-km-long Maacama fault, the lower bounds are obtained if the Maacama fault is 110 km long. Long horizontal lines indicate preferred slip rates adopted by various authors for the Maacama fault, Hayward and Calaveras faults.

Figure 2. Cumulative slip on the San Andreas fault in the Santa Cruz Mountains from earthquakes and creep since 1800. Upper dashed line, slip on the San Andreas fault since 1800 if slip were frictionless and continuous, driven by current plate boundary displacements; lower shaded areas, estimated dextral slip from earthquakes and creep for period 1800-1906. For 1989 earthquake, we use mean slip inferred from geodetic data (1.5 m, Lisowski and others, 1990). Black area above gray areas of cumulative slip represents current deficit of dextral slip, assuming that slip deficit in 1800 was negligible.
Figure 3. Estimates of potential slip in comparison with observed creep rate increases on the northern 50 km of the San Andreas fault. Potential slip is estimated using three boundary element models involving different Calaveras fault geometries: Calaveras locked, Calaveras approaching San Andreas to within 3 km, Calaveras intersecting San Andreas at kilometer 27.5. Vertical bars show estimates for the residual change in creep rate following the Loma Prieta earthquake.

Fig. 4. Displacement, d, is imposed on a vertical fault below some locking depth. Dashed lines indicate the narrowing of the resulting strain-channel with depth. For long ruptures W is constant and equal to the locking depth.
Fig. 5. Displacement as a function of rupture dimension for dislocations within the 3-D strain channel of Fig. 4. The "knee" in the curve occurs for dislocations with lengths similar to the breadth of the surface velocity field, B, which for California transform events corresponds to a fault length of ≈ 30 - 100 km.

Fig. 6. Contours of mean slip as a function of depth for vertical strike-slip ruptures propagating from the base of the seismogenic zone (basal rupture) or from half the locking depth (mid-crustal rupture). These models are driven, as in Fig. 4, by slip of 5m on a fault below a locking depth of 15 km. Small ruptures are squares with area L², long ruptures are rectangular with area LW (see Fig. 4). Approximate magnitudes were determined from the definition of seismic moment, \[ M_0 = \mu \cdot \text{slip} \cdot L \cdot W^{10} \] and the relation \[ M_w = \frac{2}{3} (\log M_0)^{10.7} \] (using c.g.s. units).

Publications and Reports:


Surface Faulting Studies

9960-12306
Element II

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Investigations

Compilation and analysis of geologic information that can be used to evaluate and mitigate hazards from faulting and associated earthquakes on part of the San Andreas fault system. The focus is on the San Francisco South quadrangle, which contains the San Andreas and related faults, many landslides, and formations of widely different response to shaking, including Franciscan bedrock, Tertiary sediments, Bay mud, and artificial fills. A 1971 MF geologic map and a 1964 Open-File map showing contours on the bedrock surface are being revised. The revised maps are being compiled in GIS (ALACARTE-ARC/INFO) format and prepared for publication on a modern base. Emphasis is being placed on late Quaternary deformation, thickness and nature of unconsolidated deposits, and earthquake-related ground failure.

Results

Made interpretive geologic section using data from the field examinations, face logs, and well logs of a tunnel recently constructed near Lake Merced. The data suggest that: 1) the San Bruno fault very probably lies northeast of the position shown by Bonilla (1971); 2) the pre-Holocene drainage system, in which Lake Merced formed, must pass north of the tunnel; and 3) a previously unknown fault probably displaces the Merced formation and perhaps the Colma formation on the west side of the lake. Positions of the upper and lower contacts of a gravel in the Merced formation suggests a vertical separation of about 5.5 m at a depth of about 30 m, and a probable strike-slip component. Also in support of a fault interpretation are (1) a change in surface geology from dune sand to Colma formation across a nearby gulley and (2) a difference in apparent dip of the Merced formation, as revealed by the well logs, on the two sides of the proposed fault. The fault may be active, since the Late Pleistocene Colma formation as well as the Merced formation may be displaced.

A cut in which the topsoil (A horizon) was displaced by a strand of the Serra fault (Bonilla, 1955, unpublished field notes) was reexamined in collaboration with J.W. Harden and T.A. Black, Branch of Western Regional Geology, and San Mateo County personnel. Erosion of the cut has revealed a different part of the fault, with a different attitude, which could not be traced to the ground surface. Seven auger holes were bored on a line about 15 m west of and parallel to the cut. These holes show a difference in thickness of the A horizon similar to that sketched in 1955, and also show that the slope of the base of the A horizon is steeper southeast of a probable fault than it is just northwest of the fault (11°-13° vs. 8°). The ground surface also shows a difference in slope, 12° southeast of the probable fault compared to 9° northwest of the probable fault. Five shallow pits were dug a short distance above the cut. These pits also show a difference in A horizon thickness. If the thickness differences shown by the holes and pits indicate faulting, the fault trace trends about N5W. However, if this is a fault strand, it is not the one mapped in 1955, but lies some 20 m to the west. (Judging by historic surface ruptures, much variation in number, attitudes and positions of strands within reverse fault zones, such as the Serra fault zone,
are to be expected.) Because of the soil's position on a slope, its thickness, and its clay content, an unambiguous age determination cannot be made. An attempt to find a suitable trenching site nearby was unsuccessful.

Continued selecting boreholes that affect the bedrock contour map, entered the data in ARC/INFO using ALACARTE, and modified bedrock contours in ARC/INFO where necessary. Examined new artificial cuts and boreholes, and modified the geologic map where necessary. Both of these activities will continue until most of the new information is acquired. Began collaborative effort with C.W. Roberts and R.C. Jachens of Geophysics Branch in preparing the bedrock surface map; they will apply gravity data in defining contours in the Colma valley area, where the bedrock has not been reached by boreholes.

The Project Chief will retire 12/31/93, but will continue the project work on a part-time basis as Geologist Emeritus.

Reports

None.

12/93
HOLOCENE SLIP RATE OF THE NORTHERN HAYWARD FAULT
AT POINT PINOLE, CALIFORNIA

Agreement No. 1434-93-G-2333
Program Element II.5
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Objectives

This project is an attempt to produce the first Quaternary slip rate for the northern end of the Hayward fault. As shown by Borchardt (1991), this end of the fault has great crustal stability, which would enable it to record evidence of the last highstand of San Francisco Bay during the Sangamon about 122,000 years ago. The highstand, about +7 m, crossed the fault in the southwestern part of Point Pinole Regional Park, planating the bedrock and removing older surficial deposits. Borchardt and others (1988) and Borchardt and Seelig (1991) speculated that over 1 km of the fault has soils, sediments, and geomorphic features dating from 122 ka. Most of the planated surface of the semi-circular embayment that crossed the fault now lies beneath colluvial, alluvial, and landslide deposits. Speculative slip rates for planated bedrock (960 m in 122 ky) and a possible alluvial fan on the abrasion platform (900 m in 114 ky) yield a slip rate of about 8 mm/yr. The objective of this project is to gather field evidence to determine the precise configuration and age of the offset embayment and its associated features.

Methods:

The first phase of the work involved the preparation of a log of the Sangamon wave-cut platform and its overlying marine and continental sediments and soils where it is exposed at Pinole Point. The second phase will involve drilling and sampling a series of boreholes designed to determine the elevation of the abrasion platform along the fault. The third phase will involve trenching, logging, and studying the suspect alluvial fan that appears to overlie the Sangamon wave-cut platform southwest of the fault.

Results

The project has been delayed for about 8 months due to difficulties in obtaining the encroachment permit for the work in the Park. Nevertheless, with the help of numerous volun-
teers, the description and logging of the exposure at Pinole Point has begun. A preliminary log of the 115-m long section shows that the abrasion platform in the Garrity Member of the Contra Costa Group is exposed for about 55 m. The platform reaches a maximum elevation of about 7 m, and has an easterly slope of about 4%. The marine sand above the platform increases in thickness from 1 m near the shoreline angle to over 2 m at the lowest exposed elevation. The soil in the overlying colluvium is similar to those described in alluvium above Sangamon coquinas elsewhere along the south shore of San Pablo Bay (Borchardt, 1988). These data were used to produce a speculative model of the Sangamon platform for refining the selection of drill sites along the fault.

One upshot of this work is the observation that much of San Pablo Bay may be relatively stable and may have a +7-m strand line completely around it. Thus an examination of the shoreline at China Camp, across the Bay directly west of Point Pinole, also showed evidence of the +7-m highstand. A small island, "Rat Rock," lies immediately offshore and has a flat surface abraded to the 20' topographic contour. In accordance with the theory being tested in this project, other islands and other parts of the San Pablo Bay shoreline are likely to yield evidence of the highstand. The strand line, of course, would reach far inland along the Petaluma Creek, Sonoma Creek, Napa Creek, and other drainages where it would provide a datum for studying sedimentation, soil formation, and tectonic deformation during the last 122,000 years.

References


Borchardt, Glenn, 1991, Vertical crustal stability between Point Pinole and Carquinez Strait during the Late Quaternary: EOS, Transactions of the American Geophysical Union, v. 72, no. 44, p. 446.


Reports Published in FY93

Borchardt, Glenn, 1992, Field trip contributions concerning the Hayward fault at Point Pinole Regional Park, Richmond,


The above volume includes the following papers related to the project:

Borchardt, Glenn, 1992, Pedochronology along the Hayward fault, p. 111-117.

Borchardt, Glenn, Lienkaemper, J.J., and Budding, K.E., 1992, Holocene slip rate of the Hayward fault at Fremont, p. 181-188.

Borchardt, Glenn, and Mace, Neal, 1992, Clastic dike as evidence for a major earthquake along the northern Hayward fault in Berkeley, p. 143-151.


Tectonic Framework and Geology of the San Francisco Bay Region

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INVESTIGATIONS

The principal earthquake-related activities, which were pursued as part of a larger Regional Geology project that is focused on the Bay region, included mapping of Quaternary deposits and of bedrock structure and stratigraphy, geologic compilation at 1:100,000, development of digital techniques for the compilation and analysis of geologic maps, cooperative work with other projects, and participation on the regional team (BAFEP).

RESULTS

New mapping of Quaternary deposits by Ed Helley in Contra Costa, Alameda, and Santa Clara Counties is about 75 percent complete (Figure 1). A few of the maps have been released as 7.5' quadrangles in Open File, but most are being compiled at 1:62,500 scale to be added to the bedrock geologic maps for Contra Costa and Alameda Counties.

Mapping of Quaternary deposits in the Patterson, Crows Landing, Midway, Tracy, Solyo and Lone Tree Creek 7.5' quadrangles has been completed by William Lettis and Associates, and released in U.S. Geological Survey Open Files. This work builds on concepts and data developed by Dennis Marchand two decades ago. The Lettis maps and those by Brian Atwater in the Sacramento-San Joquin delta provide the basis for eventually determining liquefaction potential in the Sacramento-San Joquin valleys.

One application of the mapping of Quaternary deposits has been to statistically combine this information, using GIS technology, with that on liquefaction in the Monterey Bay region (during the Loma Prieta earthquake) to prepare better liquefaction maps of the southern San Francisco Bay region and to assist in hazard recognition, risk assessment, zoning, and emergency response. Rich Bernknopf and John Sutter (Reston), Dick Pike, John Tinsley, Ed Helley, Geoff Phelps, Bill Dupré, Carl Wentworth, Bob Mark, Tracey Felger, Tom Holzer, Mike Bennett and Conyn Criley have all been involved. Jeanne Perkins, Association of Bay Area Governments, provided land use data to determine structures at risk.

Another application has been study of the direction and speed of movement of water-borne toxic materials within surficial deposits from Superfund sites in the Palo Alto to San Jose area by staff of the California Regional Water Quality Control Board. The top of the Pleistocene deposits is an aquitard, relatively impermeable, that Ed Helley contoured from the surficial deposits maps and CALTRANS borings. The aquitard surface has some unexpected relief that moves toxic fluids and water in unanticipated directions. This information will be essential in directing clean-up efforts if additional toxic waste tanks rupture during major earthquakes.

Collaborative work continues with Gary Mann and Mike Marlow on planning and interpreting marine surveys in San Francisco Bay and in nearby lakes that might conceal faults. Ultra-high resolution seismic reflection profiles reveal an astonishing number of
Fig. 1 Index map showing recent mapping of Quaternary deposits in the southern San Francisco Bay Region
faults. Ultra-high resolution seismic reflection profiles reveal an astonishing number of faults cutting Holocene sediments. In related work, Ed Helley, John Fitzpatrick and Jim Bischoff have dated oyster shells from terrace deposits at three localities on the shore of San Pablo Bay and one near Benicia. The dates range from 112 to 142 Kyrs, suggesting that the oysters were deposited during Sangamon time. The distribution and age of the oyster beds also suggest that the area from southern San Pablo Bay to Benicia has not undergone vertical deformation since the Sangamon.

USGS volunteers Larry Dickerson, John Parker, Mary Bowen and Neil Foley along with Ed Helley, Dick Pike, Conyn Criley and Earl Brabb have copied and organized approximately 50,000 logs of water wells in Santa Clara, San Mateo and San Francisco Counties in an attempt to determine the character of surficial materials around San Francisco Bay. The logs were obtained from the California department of Water Resources, Sacramento, and the Santa Clara Valley Water District in San Jose. Additional data in digital form were provided by John Fio, U.S. Geological Survey Water Resources Division, Sacramento. These data complement a similar task of digitizing water wells in Alameda and Contra Costa Counties underway by Rogers/Pacific under a NEHERP contract monitored by Tom Holzer. Knowledge of the engineering character of the surficial deposits described in the logs will help assess ground shaking and liquefaction during earthquakes.

USGS volunteer Walter Hensolt has completed a map showing the elevation of bedrock beneath the surficial deposits around San Francisco Bay from Golden Gate south to Coyote. The map is being edited for release in Open Files.

USGS volunteers and previous NEHRP recipients David Jones and Russ Graymer have completed a geologic map of the Niles 7.5’ quadrangle showing the Mission fault in relation to several newly mapped faults from Mission San Jose to Tolman Peak. The map is being edited for release in Open Files. The map is one of the building blocks for redefining the regional structure between the Hayward, Calaveras and Greenville faults. A schematic structure section prepared by D.L. Jones for the area from the Berkeley Hills to Mount Diablo, 30 km north of Niles, is provided in Figure 2.

Figure 2- Schematic structure section through the East Bay hills. JKF, Franciscan complex; GVS, Great Valley sequence; CRO, Coast Range ophiolite; Tm, marine sedimentary rocks of Miocene age; CRF, Coast Range fault. From Jones (1992).
Digital compilation of new and existing geologic maps by Carl Wentworth and Chad Nelson continues to interact with the development of ALACARTE and needed digital procedures. The user interface ALACARTE for controlling the commercial geographic system ARC/INFO (Fitzgibbon and Wentworth, 1991) has been extensively revised to work with ARC 6, with the ability to hold menus open on-screen and work with both vector and raster data. The ALACARTE code can be obtained over internet from anonymous ftp sierra (130.118.4.116; look first at the most recent ALACARTE README).

Earthquake import and cross-section routines are being incorporated into ALACARTE and have been used under our guidance by Steve Walter (USGS, Menlo Park) to prepare a seismicity map for the San Jose, California 1x2 degree sheet in ARC/INFO showing earthquakes by magnitude (dot size) and depth (dot color), with focal-mechanism beachballs for larger events colored and scaled to fit the dot. Cross sections include distinguishing cluster grouping by color. This work also involves experimental (and successful) use of a raster base through the ARC module GRID (rather than the vector format now in general use in our work in ARC/INFO). Code is also in hand to allow projection of earthquakes along azimuths specified separately by earthquake or groups of earthquakes, which will permit making cross sections that include earthquakes from faults having different strikes (assign the projection azimuth to the earthquakes as a function of strike, rather than selecting an azimuth for the cross section as a function of strike).

Methods for compiling and storing data in ARC/INFO related to the Peninsula candidate site for deep San Andreas drilling are largely in hand and disk space has been obtained and installed. Experimental plotting routines exist that can be modified to fit database content.

A digital map database of the distribution of geologic materials in the southern San Francisco Bay region has been compiled and submitted for open-file release. This has been compiled at a scale of 1:125,000 from three 1970's compilations: Brabb, geologic map of Santa Cruz County, 1989; Ellen and Wentworth, hillside materials, in press; and Helley and Lajoie, flatland materials, 1979. The database consists of lines (contacts, faults, and various other boundaries) and identities of the intervening areas (polygons, identified by unit label of the source map, stratigraphic unit reported in the source, and general age and lithology). Release will be in two parts, a short text describing the database and how to obtain it, and a compressed tar file (ssfb_ml.tar.Z) of the database in ARC coverage format that can be obtained over internet from anonymous ftp on sierra (130.118.4.116) or by sending a magnetic tape to Wentworth (1/4 inch 150 MB cartridge or 8mm 2.3 or 5.0 Exabyte).

Work has begun using the San Francisco Bay region database to extend the work of Borcherdt, Wentworth, and others (1991) to a map of the whole south Bay region showing exceedent potential for intensity of a 1906 earthquake on the San Andreas fault. Base intensities (on Franciscan rock) are determined using an attenuation function and the GIS buffer function to generate contours. These are so sensitive to the position and shape of the fault that use of a smoothed version of the source fault may yield misleading results near the fault and, thus, decisions must be made concerning which surface trace(s) to use and how to simplify the contours with increasing distance from the fault.

ALACARTE skills were used by Chad Nelsen to help Bob McLaughlin assemble a geologic map of the Loma Prieta, Laurel, Los Gatos and Santa Teresa Hills 7.5' quadrangles for the Loma Prieta Earthquake Professional Paper. One challenging task was to digitally contort the geology from an obsolete and geographically incorrect base map so that it would mesh with the other data.
Compilation and analysis of the bedrock geology for Contra Costa and Alameda Counties is in progress by Russ Graymer, Dave Jones, and Earl Brabb. Linework for Contra Costa is nearly complete. Linework for Alameda County is about 50 Percent complete.

REPORTS


ANALYSIS OF WIDE-ANGLE REFLECTION/REFRACTION RECORDINGS FROM THE BAY AREA SEISMIC IMAGING EXPERIMENT (BASIX)

Seismic Reflection Crustal Studies Project: Project No. 9930-12253

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INVESTIGATIONS UNDERTAKEN

BASIX attempted to image the subsurface geometry of the major earthquake producing faults in the San Francisco Bay Area using seismic reflection and refraction methods. BASIX obtained seismic reflection lines designed to provide a picture of the crust down to the base of the crust using a large airgun source and receivers moored to buoys in the water. At the same time, temporary seismic recorders were deployed throughout the Bay Area (see Figure 1) to record these airgun signals at large distances (wide-angles).

I have analyzed wide-angle seismic data recorded by five-day and CALNET stations during the BASIX experiment. The analysis of these records has included forward modeling and inversion of travel times.

RESULTS

My work has provided preliminary velocity and structural models for the Bay Area in the following areas: 1) the block beneath SF Bay between the San Andreas and Hayward faults, 2) the San Andreas fault in the vicinity of the Golden Gate, and 3) the crust beneath the East Bay faults between the San Andreas fault and the Great Valley.

San Francisco and San Pablo Bays

My most important finding is that San Pablo and San Francisco Bays are underlain by a prominent mid-crustal reflector at a depth of about 16-18 km (Figure 2). This reflector can be mapped from nearly the San Andreas fault to east of the Hayward fault, and may serve to couple the motions of these two faults, explaining the apparent pairing of large magnitude earthquakes that have occurred on the San Andreas and Hayward faults (Kerr, 1993). The reflector represents the top of a high-velocity (velocity about 7 km/s) mafic layer (Figure 3). The identity of the mafic layer is uncertain; it could represent a slab of subducted oceanic crust or a magmatically underplated unit. For reasons given below, we believe that at least the western half of the reflector originates from the top of a slab of oceanic crust.

The block bounded by the San Andreas and Hayward faults has only a thin 100-200 m sediment cover on the Franciscan basement rocks. Based on the relatively low-velocities within the crust, Franciscan rocks are thought to extend to a depth of about 16-18 km (Figure 3).
The crustal thickness underneath the bay is thought to be about 25-27 km. Near-vertical reflections from 9 s two-way travel time suggest that the crust is about 27 km thick.

San Andreas Fault

BASIX line 202 crosses the San Andreas fault in the vicinity of the Golden Gate. Prominent reflections from this line define an east dipping slab about 5 km thick which I am currently interpreting as a slab of oceanic crust (Figure 4). This oceanic slab extends to the east of the San Andreas fault and either flattens or is intersected by a west dipping slab of mafic lower crust, possibly representing the pre-Jurassic oceanic crust which floors the Great Valley. The depth to the top of the slab of oceanic crust beneath the fault is in close agreement with the maximum depth of earthquakes found along the fault in this location, and coupled with our previous work on the crustal structure in the vicinity of the Loma Prieta earthquake, suggests that the depth of the slab of oceanic crust may exert some control on the maximum depth of earthquakes found along the San Andreas fault on the San Francisco peninsula between San Francisco and Santa Cruz (Figure 5).

East Bay Faults and Crust

The Hayward and Rodgers Creek faults bound a 1.5 km deep basin filled with low velocity (2 km/s) sedimentary rocks. The Green Valley fault is also associated with a vertical offset of about 600 m, with the sense of motion being down to the east. From west to east between the Hayward to the Antioch faults, the top of the Franciscan plunges eastwards beneath younger sedimentary rocks to about 3 km depth (Figure 6). Velocities of the rocks to a depth of about 10 km are constrained by reversed Pg arrivals.

Unreversed Pn arrivals recorded by stations located in the Sierran foothills and eastern Great Valley suggest that the crust thins in the vicinity of the Antioch fault to about 24 km (Figure 6). Alternatively, these data, as well as compilations of previous refraction/reflection experiments by Fuis and Mooney (1990), suggest that the crust thickens towards the Coast Range and towards the Sierras. The crustal thinning occurs in the vicinity of deep seismicity near Antioch, and the depth to the base of seismicity can be traced to nearly the Moho near Antioch.

Reports Published

Page, B.M., and Brocher, T.M., Thrusting of the central California margin over the edge of the Pacific plate during the transform regime, Geology, v. 21, p. 635-638, 1993.

Abstracts Published

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Figure 1. BASIX seismic reflection lines (dashed lines) and wide-angle recorders (various symbols).

Figure 2. Map showing in dark shading the minimum geographic extent of subhorizontal mid-crustal reflections between 6 and 8 seconds two-way travel time. Reflection extents are defined by stations shown (symbols defined on side panel) from shots recorded from the BASIX lines (dashed lines).

Figure 3. One-dimensional velocity models obtained by Holbrook et al. (1992) and Walter and Mooney (1982) showing relatively small difference above 15 km. Note the presence of a high-velocity layer (7 km/s) beneath the Franciscan assemblage which we believe produces the prominent mid-crustal reflection observed at 6 seconds two-way travel time (about 18 km depth).
Figure 4. Preliminary velocity model for BASIX line 202, showing east dipping slab beneath San Andreas fault. We interpret this slab as a piece of oceanic crust, due to its dip and thickness, although we lack refracted arrivals within it, so its velocity is currently poorly known. The reflector shown in Figure 2 is labeled as a prominent reflector from the top of this slab.
SEISMICITY ALONG SAN ANDREAS FAULT

Figure 5. Seismicity along the San Andreas fault from Dietz (1992) on which we have superimposed location of slab of inferred oceanic crust determined from BASIX line 202 and from the vicinity of Loma Prieta (Page and Brocher, 1993). Note that in both cases the seismicity lies above the top of the inferred slab of oceanic crust.
Figure 6. Preliminary velocity model for BASIX lines 101-109, showing generally thin crust beneath Bay Area and Great Valley, and that the maximum depth of seismicity (squares) increases eastward towards Antioch. BASIX wide-angle receivers (filled circles) are unreversed in the Great Valley and Sierran foothills, and the crustal structure for this region is largely from previous refraction work from these areas.
Northern San Andreas Fault System

9960-12326

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Program Element II

Investigations

1. Synthesis studies of the geology, seismology, and tectonics of the San Andreas fault system, especially in northern California.

2. Advisory activities for Bay Area Regional Earthquake Preparedness Project (BAREPP) and San Francisco Bay Conservation and Development Commission (BCDC), both of which are state agencies. Similar, but intermittent and *ad hoc*, advisory activities for other state and federal agencies.

3. Research on applications of earth science-information, reviews of applications work by others, and interpretation of geologic and geophysical results for non-technical audiences.

Results

1. Completed a review of historical and field evidence concerning the location of the San Andreas fault near Shelter Cove, Humboldt County, California. This on-land location for the fault and the reported surface faulting there in 1906 have been challenged in a number of papers published since 1979. I examined archived field notes and other data from F.E. Matthes’s 1906 investigation, notes from my own (1969) and M.G. Bonilla's (1965 and 1966) field work, pre-development aerial photographs, and published work by several other investigators. The evidence supports the interpretation reported in the Report of the State Earthquake Commission (Lawson, 1908): that the 1906 right-lateral strike-slip fault rupture
was expressed on land at Shelter Cove and that this rupture is a part of a major tectonic break, the San Andreas fault.

2. Compiled and analysed data on geologic structures from slide blocks and from underlying strata in the Lakes district of Point Reyes National Seashore. Steep dips and tight folding in the slide blocks contrast with low north dips below the slide plane. These relations are inconsistent with the simple rotational slope failures previously suggested as the cause of Lakes district landslides. They are consistent with failure on a northward-dipping thrust fault, reactivated in a retrogressive sense by uplift along the southwest side of the San Andreas fault. Northwestward movement, indicative of near-fault uplift, can be dated (by woody plants in basal lake deposits) at about 3400 yr BP. Lack of significant scarp degradation and the paucity of deltaic sediment in the landslide lakes characterizes most slide blocks and suggests a similar age for much of the 20 km² extensional terrane. Relative uplift of 0.3 to 0.6 m of was observed west of the fault at Bolinas in 1906. Although no mass movements were reported in the extensional area in 1906, uplift without major sliding may have occurred there: in beach exposures above the main thrust plane, scattered erosional remnants of iron-oxide-cemented beach gravels adhere to the base of seacliffs about 1 m above high tide level. Other evidence of oblique slip, with an uplifted block west of the (dominantly right-lateral, strike-slip) San Andreas fault occurs south of the Golden Gate on the northern San Francisco Peninsula.

3. Continued to participate in activities of BCDC's Engineering Criteria Review Board. BAREPP, however, was consolidated into the California Office of Emergency Services after its October, 1992, meeting, and at that time the BAREPP Advisory Board was dissolved. Reviewed plans, regulations, proposed legislation, and research proposals and projects for federal and state agencies, and industry or professional associations. Designed and directed preparation of an exhibit display on the San Andreas fault for a local non-profit association. Served as associate editor for Earthquakes and Volcanoes.

Reports

THE PRIMARY OBJECTIVE OF THIS PROJECT IS TO DOCUMENT AND CHARACTERIZE Holocene deformation in the Puget Sound, Washington, region and develop an understanding of its structural and tectonic origins. Work during the reporting period (October 1992-September 1993) focused on refining the extent and age of late Holocene uplift in central and southwest Puget Sound (Fig. 1) that has been inferred to have been the site of a large earthquake about 1000 years ago (Bucknam and others, 1992). An important component of the work is the paleoecological analysis of sites near sea level using fossils to infer changes in relative sea level during the late Holocene in the Puget Sound region. Plant macrofossil and pollen studies are being carried out by Estella Leopold at the University of Washington, assisted by Dan Ekblaw, Gengwu Liu, and Tracy Fuentes; diatom studies are being carried out by Eileen Hemphill-Haley, U.S. Geological Survey at the University of Oregon.
RESULTS:

1) Paleoecology of coastal marshes. We have greatly expanded the paleoecological basis for inferring changes in relative sea level in the central Puget Sound region, and, thus, uplift or subsidence. In order to better interpret paleoenvironments recorded in cores and outcrops at coastal sites, Estella Leopold and colleagues mapped vegetation and made salinity and elevation measurements at the Winslow and Lynch Cove marshes to improve their understanding of the ecology of modern vegetation. They completed a detailed analysis of pollen in a core (Core A) at Winslow marsh, north of the Seattle fault, where earlier work has inferred that several decimeters of subsidence accompanied the earthquake about 1000 years ago. Their completed pollen diagram for the core shows enough detail regarding changing vegetation and marsh environments to corroborate many of the vegetation shifts inferred from seeds and other plant macrofossils in the core.

Eileen Hemphill-Haley completed a detailed analysis of diatoms in the central part of Winslow Core A that greatly strengthens our earlier inference of a sudden rise in relative sea level at the site about 1000 years ago. Diatoms were examined and counted at 5-cm intervals in a 30 cm interval of the core that includes a prominent stratigraphic change (at a depth of 110-125 cm) marking the inferred sudden rise. Diatoms in the lower 10 cm of the interval (at a depth of 125-135 cm) consist of a mix of fresh-brackish bog and fresh-brackish marsh species. At 125 cm, there is an increase in a group of diatoms that are transitional between brackish bog and salt marsh species, an increase in salt marsh species, and a small relative decrease in fresh-brackish species. From 115 to 105 cm, salt marsh species dominate the assemblage.

2) Extent of the central Puget Sound uplift. We further defined the extent of this uplift by photogeological mapping and reconnaissance field studies of a terrace associated with the uplift. The mapping shows that the terrace, which is several meters above present high tide, extends nearly continuously from Restoration Point (R on Fig. 2) along the south end of Bainbridge Island. The terrace also extends along the coast south of Bainbridge Island to the vicinity of Bremerton, and along both sides of Puget Sound to a point nearly 10 km south of the Seattle fault. Although nearly all of the terrace has been utilized for homesites, its geomorphic expression is clear and enough of it is accessible to provide opportunities to measure its present elevation, which will allow estimation of the amount and pattern of uplift.

Figure 2. Extent of marine terrace in Seattle uplift area shown by heavy line and dots. Approximate height of terrace above high tide, in meters, shown at upward pointing triangles.
3) **Possible tsunami sand at Hood Canal.** We developed evidence that a layer of sand that underlies 1 to 2 meters of peat at an uplifted tidal flat at Lynch Cove at the southern tip of Hood Canal, Washington, may have been deposited by a surge of water coincident with the uplift about 1000 years ago. The typically very-fine to fine-grained sand forms a widespread layer as much as 80 cm thick that overlies tidal flat mud. The sand locally contains rounded fragments of wood and bark. A critical piece of evidence that the sand was transported by a surge of water is a log that dates from the time of uplift and which is partly embedded in the sand. The basal meter of the 50-cm-dia Douglas fir log has partially eroded out of peat at the seaward edge of the marsh at Lynch Cove. The lowermost part of the horizontal log is embedded in the layer of sand beneath the peat; the broken stubs of its roots extend downward about 35 cm through the sand to the level of tidal flat mud below the sand. Bark is well preserved on the underside of the log but is rolled off most of the upper part. Analysis of 10 rings from the log, probably rings 70-80 below the bark, gave a conventional radiocarbon age of 1,100 ± 60 $^{14}$C yr B.P. (Beta-63337). Analysis of the tree-ring chronology of the log by Gordon Jacoby (Lamont-Doherty Earth Observatory) may further refine the age of the outer tree rings. The tree must have died at or shortly before the time of the uplift event at Lynch Cove. If, for example, the tree toppled from a bluff onto a beach prior to the uplift and was subsequently transported by a surge of water onto the uplifted tidal flat, the age is a maximum for the time of uplift. The good preservation of the bark and the lack of abrasion suggests that the tree did not die very long before it was transported to the site, probably no more than a decade before uplift. Alternatively, the tree may have been uprooted as a result of shaking by the earthquake that produced the uplift, toppled onto a shoreline, and was then transported by a surge of water onto the uplifted tidal flat. In this case the outer tree ring would date the time of uplift.

4) **Age of uplift in southwestern Puget Sound region.** Radiocarbon ages reported in Bucknam and others (1992) limited the time of uplift at Lynch Cove to between 1170 ± 90 $^{14}$C yr B.P. and 1420 ± 70 $^{14}$C yr B.P. Additional work shows that a distinctive plant, *Triglochin maritimum*, locally colonized the uplifted tidal flat at Lynch Cove. Although typically a salt marsh plant, the species likely was initially successful on the saline uplifted tidal flat. Leaf bases of the plant are embedded in growth position in the top of the sand overlies uplifted tidal flat mud. Basal peat adjacent to and overlying the *Triglochin* leaf bases lacks salt marsh diatoms and is rich in upland plant seeds and pollen. The high precision radiocarbon age of 1132 ± 17 $^{14}$C yr B.P. (QL-4658) for the leaf bases, determined by Minze Stuiver at the University of Washington, is a minimum age that probably postdates the time of uplift by no more than several decades. Additional dating and tree-ring study of the log described above may allow estimation of the time of uplift to within a few years.

5) **Additional evidence of uplift in southwestern Puget Sound region.** We further defined the extent of the area of uplift in the southwestern Puget Sound region by means of study of a salt marsh near the Skokomish River on Hood Canal (at the bend in Hood Canal, Fig. 1). As at other sites in the southwestern area of uplift, woody, freshwater peat abruptly overlies mud, which is interpreted as evidence of uplift. A conventional radiocarbon age of 1050 ± 60 $^{14}$C years B.P. (Beta-61785) from the basal peat is similar to basal peat ages from other sites in the uplift area.

**REPORTS PUBLISHED**


Investigations

The Global Seismograph Network (GSN) presently consists of the Global Digital Seismic Network (GDSN) 3 stations; the China Digital Seismic Network (CDSN) 11 stations; the Incorporated Research Institutions for Seismology Network (IRIS/GSN) 31 stations and the Worldwide Standardized Seismograph Network (WWSSN) 60 stations. Support is furnished at a level needed to keep the GSN at the highest percentage of operational time in order to provide the improved geographical coverage with analog and digital data from highly sensitive short-period and very broadband seismic sensor seismograph systems. This support includes provision of operational supplies, replacement parts, repair services, modifications, on-site system installation, maintenance, training and system calibration.

Results

The GSN continues with a combined total of 105 WWSSN/ASRO/DWWSSN/CDSN/IRIS-1/IRIS-2 stations. Global seismic data coverage is provided to the National Earthquake Information Center (NEIC) and to other data centers and research organizations throughout the world.

IRIS-2 seismograph systems were installed at eleven locations: San Pablo, Spain (PAB); Palmer Station, Antarctica (PMSA); Canary Islands, Spain (TBT); San Juan, Puerto Rico (SJG); Kevo, Finland (KEV); Afiamalu, Western Samoa (AFI); Port Moresby, New Guinea (PMG); Yakutsk, Russia (YAK); Petropavlovsk, Kamchatsky (PET); Magadan, Russia (MA2); and Adak, Alaska (ADK).

On-site maintenance visits were required at the following locations: Albuquerque, New Mexico (ANMO); Guam, Mariana Islands (GUMO); San Pablo, Spain (PAB); Charters Towers, Australia (CTAO); Narrogin, Australia (NWAO); Chiang Mai, Thailand (CATO); and Taipei, Taiwan (TATO).

Site surveys were performed at the following locations: San Juan, Puerto Rico (SJG); Quetta, Pakistan (QUE); New Delhi, India (NDI); Manaus, Brazil (PTGA); Tsumeb, Namibia (TSN); Lusaka, Zambia (LSZ); and Nairobi, Kenya (NAI).
Seismic-Geophysical Studies

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Investigations Undertaken

A seismic refraction investigation of the San Francisco Bay Area was completed in May 1993. The seismic survey consisted of three seismic transects, one along the western side of the Bay, a second along the eastern side of the Bay, and a third across the Bay in the vicinity of Menlo Park (Fig. 1). An additional seismic array was placed to the south, across the epicentral areas of the 1989 Loma Prieta earthquake. Numerous chemical explosions were fired into the seismic arrays in order to determine the velocity structure of the San Francisco Bay area, useful in properly locating the seismicity of the region and determining the seismic propagation and attenuation characteristics.

Investigations related to the propagation and attenuation characteristics of the central United States were also continued. Weak ground motions were compared with strong ground motions from other regions to develop expectations of ground shaking in future New Madrid earthquakes.

Results:

Data from 1993 Bay Areas seismic investigation were processed and prepared for computer modeling routines. The data from the East Bay are being modeled, but preliminary models from the West Bay show that the crust dramatically thins to the north, under the city of San Francisco. Computer modeling shows that the thinning crust caused seismic energy from the 1989 to be reflected and focused under the cities of San Francisco and Oakland. This reflected energy accounts for the great damage in those cities, with lesser damage between the epicenter and those cities. Preliminary evaluation of weak ground motions from the explosions shows what should be expected for future earthquake in along the Hayward Fault in the East Bay (Figs. 2 and 3). Those data show that cities east and north of the Hayward Fault are likely to experience the greatest damage from an earthquake centered on the southern Hayward Fault.
The continued work in the New Madrid region shows that seismic energy propagation is much more efficient in that area than in the San Francisco Area and that greater damage is to be expected over a much wider region in the event of a M 7.1 earthquake.

Reports Published:

Catchings, R. D., and W. M. Kohler, 1993, Preliminary results from a 1993 seismic survey of the San Francisco Bay: East Bay Results, EOS, Trans. AGU, 74, 413

Kohler, W. M. and Catchings, R. D., 1993; A P-wave velocity model of the Western San Francisco Bay Area from seismic refraction measurements, EOS Trans., AGU, 74, 414


Fig. 1
Location of the seismic profiles acquired during May, 1993. The letters A-A', B-B', C-C', and D-D' show the location of the recording arrays. The dots indicate individual recording sites. The black arrows show the lines from which the data of figures 2 and 3 were taken. Shot points are shown as black dots.
Amplitude-Distance Relations

Fig. 2: Peak amplitude-distance relations for seismic waves propagation across the San Francisco Bay with the shot located at shot point 3 (see fig. 1). Note that the relative peaks occur near the towns, which are within sedimentary basins. Areas east of the Hayward Fault experience greater levels of ground motion.
Figure 3
Peak amplitude-distance relations for seismic waves propagation along the Hayward Fault with the shot located at shot point 3 (see fig. 1). Note that the high amplitudes are observed in the northern part of the Hayward Fault, where the largest cities are located. San Jose, another large city, is located within a low-amplitude zone, suggesting less damage from an earthquake located in the Fremont/Union City area.
Instrumentation and Testing of Structures

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Investigations

1. The process of selection of structures recommended for strong-motion instrumentation has continued in Memphis (Tennessee), Reno (Nevada), Hawaii, and Puerto Rico.

2. Cooperative instrumentation of building in Olympia, Washington, is completed.

3. Instrumentation of building in Seattle is completed.

4. Cooperative instrumentation plans of the U.S. Court of Appeals Court Building in San Francisco is underway. This building is being seismically upgraded by base isolation.

5. Efforts have been made to initiate and make plans for instrumentation of a building in Puerto Rico in cooperation with University of Puerto Rico (Mayaguez) and NIST. The building will be instrumented for both earthquake and hurricane hazard.

6. Plans have been made to deploy free-field instruments in Puerto Rico in cooperation with University of Puerto Rico (Mayaguez). Necessary hardware have been acquired.

7. Studies of records obtained from instrumented structures during the 1987 Whittier and 1989 Loma Prieta earthquakes have continued. Journal and conference papers have been prepared.

8. Cooperative project with NIST on low-level amplitude tests of instrumented structures has been completed. Journal and conference papers have been prepared.

9. Plans are being made to convert the wind-monitoring system at Theme Buildings in Los Angeles into strong-motion monitoring system.
10. Plans are made to deploy a special purpose strong-motion array to study soil-structure interaction. This will be implemented when funds are available.

Results

1. Papers resulting from study of records obtained from structures are prepared, published in referred journals, and presented in conferences.

2. Invited talks given at conferences, workshops, and as outreach.

3. As funds are available, instrumentation efforts continue.

Reports


Celebi, M., 1993 (authored Chapter 3, Strong motion; Chapter 4, Earthquake code for design; Chapter 6, Industrial facilities; Chapter 9, Reconstruction; and contributed to Chapter 1, Introduction and Chapter 5, Buildings), in Erzincan, 270


Late Quaternary slip rates on active faults of California

9960-10316, 11316, 12316

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Program element II

Investigations

1. Recently active traces of the Calaveras fault zone at Tres Pinos and San Felipe Creeks, California (K.J. Kendrick, J.W. Harden, M.M. Clark).

2. Recently active traces of Owens Valley fault zone, California (Sarah Beanland, EDS, IGNS, New Zealand; Clark).

3. Degradation of fluvial terrace risers along Lone Pine Creek, San Bernardino County (Kendrick, with J.B.J. Harrison, L.D. McFadden [UNM] and R.J. Weldon [UOR]).


5. Late Quaternary evolution of the San Timoteo Badlands region, southern California (Kendrick, with S.G. Wells [UCR], D.M. Morton, and L.D. McFadden [UNM]).


Results

2. Owens Valley fault zone. See v. 33, p. 202-3 of this publication for results summarized from our report, USGS Bulletin 1982, in press, listed below. This Bulletin features a 1:24,000-scale strip map of the Owens Valley fault zone, a table of characteristics and measurements of active traces at 40 sites along the fault zone from Owens Lake to north of Big Pine, and text.


4. Late Quaternary slip rates of the 11 or so recognized active range-front faults of the Sierra Nevada from Owens Lake northwestward to Carson Valley show enough variation with time and location that a proper understanding of slip behavior of these faults may require slip histories at many places for each. Late Quaternary traces of these normal faults vary in length from 13 to 45 km. Most faults trend more northerly than the ~NW trend of the range front. The faults are separated by <5 to >20 km of apparently unfaulted terrain; many have echelon overlap. None of the faults has a significant component of strike slip, including those of Owens Valley. The largest late Quaternary slip rates (>2 mm/yr) occur on the Hilton Creek fault at Long Valley and 20 km to the north on the Mono Lake fault. Slip rates >1 mm/yr occur on at least one fault north of Mono
that increase northward from the south end of the fault, but stay constant through time at a site.
The slip rates are 0.1 to 0.4 mm/yr near the south end; 0.1 to 0.8 mm/yr at Hilton Lakes, 3 km
to the northwest; 1.4 to 3 mm/yr at McGee Creek, 9 km farther northwest; and 1.1 to 2 mm/yr
at Tobacco Flat, 5 km farther northwest in Long Valley and >15 km from the north end of
the fault. At McGee Creek, slip rate since 10 - 15 ka is 1.3 - 2.5 mm/yr; since 13 - 20 ka, 1.4 -
2.6 mm/yr; since 25 - 40 ka, 1.4 - 4.2 mm/yr; and since 65 - 140 ka, 1.1 - 3.5 mm/yr. The
apparently uniform rate through time at McGee Creek (and also at Hilton Lakes and Tobacco
Flat, but for fewer periods; the south end site is for only one period) is interesting, but not yet
convincing, mainly because of uncertain dates.
In contrast, both the Independence fault at Sawmill Creek at Owens Valley and the Silver Lake
fault next to Mono Lake show not only large changes in slip rate along strike, but also large
changes in those rates with time. Although Bursik and Sieh (1989) relate the rate changes on
the Silver Lake fault to nearby dike intrusions, the existence of such changes should caution us
not to confidently assume constant rate with time on other range-front faults.
Indeed, we still do not know how many of these range-front faults or their segments might be
involved in one earthquake or earthquake sequence. We need many careful studies before we
can characterize late-Quaternary activity along the Sierran range front and its varied faults.

5. Kendrick described 20 soils in San Timoteo and Reche Canyons in San Timoteo Badlands.
She analysed these soils in the lab and estimated their soil development and rubification indices.
She used these indices and the amount and composition of iron oxides to estimate ages of
geomorphic surfaces associated with these soils. These ages, combined with offsets of clasts
determined by D.M. Morton and J.C. Matti, yield slip rates of 10 ± 3 and 19 ± 6 mm/yr for
this part of the San Jacinto fault. These slip rates are larger than previous estimates.
Prepare report, K.J. Kendrick, L.D. McFadden, and D.M. Morton, Soil development in the
San Timoteo Badlands region; implications for slip on the San Jacinto fault (intended for GSA
Bulletin).

6. Clark helped organize, support, and coordinate the field search for ground ruptures in Eureka
Valley by Hecker, Pezzopane, Casserly, and Berman following the M 6.2 earthquake of 17
May 93.

Reports

Beanland, Sarah, and Clark, M.M., 1993, Late Quaternary history of the Owens Valley fault zone,
estern California, and surface rupture associated with the 1872 earthquake: Geol. Society
America Abstracts with Programs, v. 25, no. 5, p. 21.

Harrison, J.B.J., Kendrick, K.J., McFadden, L.D., and Weldon, R.J. III, The influence of
terrace scarp degradation on soil-profile development, Cajon Pass, southern California:
Catena, in press.

876.
TITLE: Late Cenozoic Deformation, Northern California-Southern Oregon Convergent Margin

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PROGRAM ELEMENT: II 1, 4, 5 (PN)

Principal project objectives are to characterize the late Cenozoic structural architecture and tectonic history, to document the history of Holocene paleoseismicity and tsunami inundation, and to determine the seismic potential of the southern Cascadia subduction zone (CSZ), southern Oregon and northern California. These studies are important to an understanding of CSZ tectonics because only in this region does the active accretionary fold and thrust belt overlying the subduction zone extend onland (fig. 1). This geometry allows 3-dimensional offshore seismic-reflection studies of accretionary margin structure and the relationship of this structure to the subduction zone to be linked directly with detailed studies on land of the deformational styles and rates, and paleoseismic histories of the principal seismogenic structures.

INTRODUCTION

Seismic-reflection studies of offshore northern California and southern Oregon show that the southern CSZ is dominated by west-verging thrust and reverse faults (fig. 1; Clarke, 1992). This deformation expresses Gorda-North American plate convergence, strong partial interplate coupling, and contraction across the North American plate margin. Deformation and paleoseismicity associated with the principal thrust systems — the Little Salmon fault and Mad River fault zone — have been extensively studied on land in the Humboldt Bay, California, area (e.g., Carver, 1987; Carver and Burke, 1992), and a chronology of late Holocene coseismic deformation associated with these and related structures has been assembled (Clarke and Carver, 1992; Valentine and others, 1992).

Investigations conducted during the past year were directed principally at two lesser known parts of the northern California margin, as well as at refining knowledge of major structures in the Humboldt Bay-Arcata Bay area. This work focused on (1) conducting collaborative offshore high-resolution seismic-reflection profiling (Sam Clarke) and onshore studies of Quaternary deformation (Angela Jayko) to refine knowledge of the structure and Quaternary tectonic history of the Crescent City platform, and (2) obtaining high-resolution seismic-reflection data from the area of offshore deformation associated with the April 25, 1992, Cape Mendocino earthquake.

Crescent City area:

Previous field reconnaissance in the Crescent City-Smith River area suggests that the complex system of thrusts, back thrusts and fault-related folds mapped offshore from MCS data is represented onland by marine-terrace deformation similar to that documented from the Humboldt
Bay area. At least four such terraces have been identified from preliminary study of soils, and it is likely that soil chronostatigraphy could be used to establish Quaternary terrace deformation styles and rates. In addition, preliminary sites for coring to establish a chronology of coseismic subsidence events have been identified north and east of Crescent City. This coring should provide event ages for comparison with coseismic deformation histories in the Coos Bay, Oregon, and Eureka, California, areas, thus linking paleoseismic histories along this 300-km-long, previously little-studied coastal segment of the southern CSZ. However, detailed mapping of Quaternary deformation, onshore and offshore, is a prerequisite for future coseismic subsidence and marine-terrace deformation studies in this area. Such mapping has been hampered in the past, offshore, by the inability of an ocean-going vessel to tow a hydrophone streamer into rocky inshore areas landward of St. George Reef, north-northwest of the Crescent City platform, and, onshore, by the pervasive cover of dune sand on the Crescent City platform. Our objective in this part of the study (and principal objective for 1993) was to carry out detailed offshore small-boat high-resolution seismic-reflection profiling in previously inaccessible inshore areas in collaboration with detailed examination and, where possible, mapping of Quaternary structure on land. By projecting offshore structures landward onto emergent parts of the Crescent City platform, we anticipated that we could obtain a more coherent view of Quaternary deformation over the entire platform than would be available through the separate application of either method.

Humboldt-Arcata Bay area:

Coseismic deformation chronologies have been obtained from trenches across the Little Salmon fault and from the Freshwater syncline (Mad River Slough) on the northern margin of Arcata Bay (Clarke and Carver, 1992), from the South Bay syncline (Valentine and others, 1992), and from the south flank of the Eel River syncline (Li, 1992). High-resolution seismic-reflection profiling in support of these studies was carried out late in 1992. This profiling located youthful traces of both the Little Salmon and the Table Bluff thrust systems, and provided useful evidence regarding the specific structural context of these deformation chronologies. While additional Arcata-Humboldt Bay profiling was not a primary objective of the FY 93 research program, additional lines were run in the bays during periods of inclement weather offshore.

False Cape-Cape Mendocino-Punta Gorda area:

Coseismic deformation associated with the April 25, 1992, Cape Mendocino earthquake has been studied extensively on land (e.g., G. Carver—coastal uplift determined from displaced intertidal communities; D. Merritts—deformation determined from surveys of the Holocene marine terrace; M. Lisowski—GPS-based geodetic surveys; R. Stein—releveling surveys). However, half or more of the area of deformation lies offshore. Anecdotal evidence exists of offshore uplift and seafloor failures in the head of Mattole Canyon, off Punta Gorda. Moreover, this earthquake has raised questions concerning the location of the recently mapped (Clarke, 1992; McLaughlin and others, in press) Gorda-North America plate boundary in this area. The earthquake was a thrust event in the lower part of the North America plate (Oppenheimer and others, 1993), and related uplift should have been mostly or wholly within the North America plate. However, measurements from the onland studies noted above suggest that uplift extended across this plate boundary and affected an area that is ostensibly underlain by both plates (fig. 1). Either the boundary extends farther southeastward than is presently mapped, or it is more complex than is presently envisioned.

Our objectives were to map youthful faulting associated with the onland Russ, Capetown, Petrolia and Cooskie fault zones (the latter two faults have been postulated by Clarke [1992] and McLaughlin and others [in press] to incorporate major plate boundaries in the Mendocino triple junction area), determine the extent and nature of seafloor failures and, if possible, to resolve the offshore uplift signal from the Cape Mendocino earthquake. This work is complimentary to deep structural studies of the MTJ proposed under the Deep Continental Studies program, as it primarily
addresses the areal distribution of youthful deformation in the Cape Mendocino earthquake source region and Mendocino triple junction area. This work also compliments onshore studies of coseismic deformation and proposed EDGE and OEVE seismic-reflection and refraction studies in this area.

RESULTS

Field study of Quaternary deformation on the Crescent City platform was carried out by Angela Jayko (BWRG) during August-September, 1993, and is the subject of a separate report ("Quaternary deformation in response to subduction and triple junction migration, Crescent City, California") in this volume.

Seismic-reflection data collection was carried out during September, 1993, and the transcription of digitally-recorded data took much of the following month. We collected about 350 line-km of consistently good-to-excellent quality data, largely from the Crescent City area (fig. 2). As interpretation of these data has just commenced, results reported here will focus partly on aspects of the operation itself, as small boat-of-opportunity inshore seismic work would seem to be of potentially great benefit to future NEHRP near-coastal work.

Seismic-data collection employed a GEOPULSE single-plate transducer as a sound source and an ITI 12-element hydrophone streamer that is optimized for shallow-water use. Data were recorded in both analog (using a GEOPULSE receiver and EPC 9800 recorder) and digital (using the French-designed ELICS digital data-acquisition system) formats. This permitted simultaneous recording of data at vertical exaggerations of about 13-14:1 for the analog data, and 3.5:1 for initial playback of the digital data — a range that greatly aids in interpretation. The digital data will undergo further processing as needed. Subbottom penetration of 75-150 m with resolution of ~2 m was typical.

A 36-foot commercial fishing boat (aptly named the "Jumpin Jack") was chartered and modified to house the electronics, spare parts, generators, etc., for the operation. Position data was supplied by an integrated navigation display based on GPS. Initial problems related to the use of sophisticated electronics and their supporting systems in a rough, wet environment were eventually overcome. Significant limitations were imposed, on occasion, by wind and sea conditions that precluded data collection from a small boat, and by the relatively low transit speeds of which the boat was capable. The former is a condition that must be lived with in this region — about 25-30 percent weather downtime for offshore work during the best part of the season is a fact of life on much of this coast — and the wind and water conditions always had an influence on how and where data were run. Data collection was at 3-3 1/2 kts, as engine noise was recorded at engine operating speeds greater than about 500 RPM, but this was a relatively minor difficulty as the optimum speed for data collection is ~4-4 1/2 kts in any case. Nonetheless, "scoping" the acoustic properties of the operating platform prior to acceptance is recommended. Transit time is a major consideration when conducting more-or-less daylight small-boat operations from a port. Transit speed can be improved relatively easily (finer-pitched propeller and a large stock of scopolamine patches), but it is important in planning to factor in realistic daily transit times (in the Cape Mendocino area, transit time ~ 7-8 kts) to the work area was ~ 4-4 1/2 hours, and the return was ~ 6-6 1/2 hours against wind, seas and current, which limited time for data collection) or to provide for "anchoring out" or alternate ports to improve the ratio of transit to work time. However, all-in-all this operation proved feasible and highly cost effective (~ $40-$50/line-km, OE cost), acquiring consistently good-to-excellent quality structural and stratigraphic information that is largely unavailable to the field observer on land.

Results of preliminary field interpretation of the data obtained indicates that, (1) at Crescent City, the Plio-Pleistocene section offshore can be subdivided and correlated with the partly equivalent section that overlies a wave-cut platform on acoustic basement (Franciscan Complex) on land; the
pre-Holocene offshore section is complexity folded and, although fault planes are not readily apparent in the data, fold forms suggest that the offshore is underlain by thrusts and back thrusts. Fold axes can be traced with confidence landward virtually to the beach. This will provide a basis for interpreting Quaternary deformation on land that is unavailable from field mapping due to the pervasive cover of dune sand on the platform. It will also provide a basis for selection of coring sites to produce a coseismic deformation history from this area; (2) in Arcata-Humboldt Bays, additional line-crossings of Little Salmon fault will provide constraints on the location and orientation of individual splays of faults of this complex fault system; and (3) in the False Cape-Mendocino-Punta Gorda area, structures associated with the newly described False Cape terrane (McLaughlin and Aalto [HSU]) were imaged, and extension of this terrane can be mapped in the offshore. In the deformation area of the Cape Mendocino earthquake, the wave-cut pre-Holocene platform on Franciscan Coastal belt rocks is warped, tilted north in the vicinity of Mattole Canyon, and is elevated south of the canyon axis. The relationship of this deformation to the earthquake, and to possible tectonic wedging at depth is under study.

A comprehensive report of findings from the profiles obtained during this operation will be made available during FY 94, following the completion of interpretation of the records obtained and collation of the data.

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McLaughlin, R.J., Ellen, S.D., Clarke, S.H., Jr., and Cyr, K., Geologic map of the Cape Mendocino 1:100,000 Quadrangle, California (in review).

McLaughlin, R.J., Ellen, S.D., Clarke, S.H., Jr., and Cyr, K., Geologic map of the Eureka 1:100,000 Quadrangle, California (in review).
Figure 1: Simplified structural map of the southern Cascadia subduction zone-Mendocino triple junction region. Diagonal ruling indicates probable area of uplift associated with April 25, 1992, Cape Mendocino earthquake. Abbreviations are as follow: Locations — CB, Cape Blanco; CC, Crescent City; CM, Cape Mendocino; E, Eureka; F, Ferndale; H, Honeydew; P, Petrolia; PG Punta Gorda. Structural features — BFZ, Blanco fracture zone; CBF, Coastal belt fault; CSZ, Cooskie shear zone; ERS, Eel River syncline; GR, Gorda Ridge; LSF, Little Salmon fault; MF, Mendocino fault; MRFZ, Mad River fault zone; MSZ, Mattole shear zone; MTJ, Mendocino triple junction; PSZ, Petrolia shear zone; SAF, San Andreas fault; SCSZ, southern Cascadia subduction zone deformation front; TBF, Table Bluff fault; dotted line indicates west edge of SCSZ interplate coupling.
Figure 2: Location map of offshore seismic-reflection profiles collected during FY 93. Heavy lines indicate profile locations. Locations are: B - Brookings; CC - Crescent City; CM - Cape Mendocino; E - Eureka; FC - False Cape; PG - Punta Gorda.
PURPOSE OF PROJECT

This project focuses on studies that provide basic geologic information on the distribution, characteristics, and frequency of large earthquakes in the central interior of the United States with particular emphasis on the New Madrid seismic zone. The overall objective is to contribute to a better understanding of the structural features that might produce large, potentially damaging intraplate earthquakes. Project members during this reporting period include Donley S. Collins, Anthony J. Crone, Richard L. Dart, and Sharon F. Diehl.

INVESTIGATIONS

D.S. Collins completed a comparison of the stratigraphy, fossil data, and insoluble-residue data from the Strake Petroleum-No. 1 Russell drill hole in Pemiscot Co., Missouri with similar data from the Dow Chemical-No. 1 Garrigan and the O.W. Killam-No. 1 K. Pattinson drill holes. These data were also compared with similar data from other deep drill holes in the New Madrid region to assist in correlating and clarifying the structural relations between Lower Paleozoic rocks in the Reelfoot rift and to interpret the stratigraphy, depositional history, and tectonic framework of the Lower Paleozoic rocks in this region.

A.J. Crone, in collaboration with E.S. Schweig (USGS, Memphis) and M. Giardino (Univ. of Torino, Italy), continued efforts to obtain new paleoseismic evidence of large prehistoric earthquakes in the New Madrid seismic zone (NMSZ) by excavating exploratory trenches at sites where modern tectonism may have deformed geologically young, shallow sediments. They concentrated on areas where previous USGS studies had collected high-resolution seismic-reflection data which revealed the presence of shallow deformation. Four general areas were initially targeting based on the shallow reflection data: 1) the Crittenden County fault zone in northeastern Arkansas, 2) the area near Marston, Missouri where historical accounts report the formation of waterfalls in the Mississippi River following the February 7, 1812 earthquake, 3) the flanks of Crowley's Ridge, which is the most prominent topographic feature in the northern Mississippi embayment, and 4) the Bootheel lineament, which is an enigmatic feature that extends more than 100 km south-southwest from near New Madrid, Missouri to near Blytheville, Arkansas. Following reconnaissance field studies in March, 1993, trenching efforts focused on the Crittenden County and the Bootheel lineament sites. The U.S. Nuclear Regulatory Commission provided partial support for these studies.

In September, 1993, three east-west-trending trenches were excavated across the Bootheel lineament at a site (the Jenkins site) about 7.4 km (4.6 mi) west-southwest of Steele, Missouri (N°1/2, NW, SW, T. 17 N, R. 11 E, Pemiscot Co., Missouri; USGS Denton, MO 7½-minute topographic quadrangle). Here, the Bootheel lineament is narrow and easily recognized in the field. We also excavated a 49-m-long, east-west-trending trench across the Crittenden County fault zone in northeastern Arkansas (NW, NW, SE, Sec. 22, T. 8 N., R 7 E., Crittenden Co., Arkansas; USGS Heafer, Ark. 7½-minute topographic quadrangle) where geophysical data indicate the presence of very shallow subsurface deformation.
R.L. Dart and H.S. Swolfs completed their structural analysis of the Reelfoot rift based on detailed contour mapping of the Precambrian basement surface. The manuscript summarizing this work will be submitted for publication as a journal article.

S.F. Diehl studied authigenic minerals and microstructural fabric of rocks from the Reelfoot rift and adjacent terrains to help to characterize the structural history of the rift. These studies provide evidence of multiple deformational and fluid-migration events. She examined oriented, polished samples from the English Hill fault in Grays Point Quarry at the northwestern edge of the Mississippi embayment in southeastern Missouri. This fault approximately coincides with part of northeast-trending boundary the Reelfoot rift. The samples contain abundant calcite- and dolomite-filled veins; these veins offer insight into the episodes of fluid-migration that are associated with fault activity in the region.

She also obtained heavy mineral separates from four samples of the lamprophyric dikes in the Dow Chemical Co.-No. 1 Wilson well. The dikes are thought to be late Paleozoic in age based on the dates of similar lamprophyric material elsewhere in the region (Lewis and Mitchell, 1987). These dates, combined with dates from studies in the southwestern part of the rift by Marta Flohr (Branch of Eastern Regional Geology, Reston), will clarify the timing of igneous activity in the rift. Samples of igneous dikes from the Killam and Strake drill holes have been collected for whole rock dates. Whole rock dates are less desirable to dating specific mineral constituents, but the quantity of igneous rock in these samples is too small for any other currently available dating technique.

**Related Investigations**

Although not directly funded by NEHRP, Crone and M. N. Machette (Branch of Earthquake and Landslide Hazards), in conjunction with J.R. Bowman (formerly at Australian Geological Survey Organization, Canberra), completed a manuscript describing the long-term behavior of faults in stable continental settings. This report is based in part of the results of their studies of Australia intraplate earthquakes, which was originally supported by funds from the USGS G.K. Gilbert Fellowship program. Crone and Machette also presented these results at the 1993 Annual Meeting of the Geological Society of America.

**RESULTS**

(Collins) Comparison of the stratigraphy, fossil data, and insoluble residue data from the Strake Petroleum-No. 1 Russell drill hole (Strake drill hole) to similar data from the Dow Chemical-No. 1 Garrigan (Garrigan drill hole) and O.W. Killam-No. 1 K. Pattinson (Killam drill hole) drill holes and to other deep drill holes such as the Dow Chemical-No. 1 Wilson drill hole (Wilson drill hole) in the New Madrid region yielded the following major conclusions:

1. Insoluble residue data cannot be used to confidently correlate siliciclastic rocks in the Reelfoot rift with contemporaneous carbonate rocks on the platforms adjacent to the rift.
2. Insoluble heavy minerals suggest that regionally, both high-grade metamorphic rocks (mainly from the Central Missouri high) and igneous rocks (perhaps from the St. François Mountains) supplied siliciclastic sediment to the rift during Cambrian and Ordovician time.
3. Metamorphic minerals are not present in the insoluble heavy minerals from the Killam and Garrigan drill holes, which are located in the deeper part of the Reelfoot rift. In contrast, metamorphic minerals are present in the Strake drill hole, which is located near the northwestern edge of the rift. These relations imply that the carbonate platform prevented metamorphic minerals from being transported to the interior of the rift basin.
4. Lithologies in the Strake drill hole indicate that the deposition of deep-water siliciclastic rocks was followed by deposition of shallower-water carbonate rocks. In contrast, in the Killam drill hole (about 20 km to the southeast) and in the Garrigan drill hole (about 62 km to the south-southwest), all of the equivalent-age rocks are siliciclastic lithologies that were deposited in deep water. These observations indicate that the rocks in the Killam and Garrigan drill holes
were deposited in a structural low, whereas, rocks in the Strake drill hole were deposited at a structurally higher elevation on or near the flank of the rift.

5. The correlation of biostratigraphic data between the Strake, Garrigan, and Wilson drill holes indicates the presence of one or more faults that have a down-to-the-southeast displacement between the Garrigan and Wilson drill holes. These faults have cumulative throws of about 1,432 m (4,700 ft) between the Garrigan and Wilson drill holes and about 2,408 m (7,900 ft) between the Strake and Wilson drill holes.

(Crone)

**Bootheel Lineament Trenches**

At the Jenkins site, the Bootheel lineament has a general trend of N. 24° E. (024°) and is marked by an area of light-colored, relatively well drained soil to the west and an area of dark-colored, poorly drained soil to the east. Topographically, the western side of the lineament is about 30 cm higher than the eastern side. The sharp definition of the Bootheel lineament at this site allowed us to trench across the entire feature and to define stratigraphic and structural differences on both sides of the lineament. We excavated three subparallel, east-west-trending trenches that were spaced approximately 15 m apart. Trench 1, the longest and northernmost trench, was about 73 m long and extended across the entire feature. Trenches 2 and 3, were about 22 m long and 16 m long, respectively, and span the portion of the lineament where the most prominent liquefaction features are present in trench 1.

The deposits in the Bootheel lineament trenches consisted of a fining-upward sequence fluvial sediments that are overlain by a sequence of sand-blow deposits. The lowermost unit of the fluvial sequence is a well-sorted, medium- to coarse-grained, quartzose sand that laterally grades into a finer grained silty sand facies. The basal sand is over lain by a massive, light gray to very pale brown, slightly silty, medium- to fine-grained sand. Upward, the silt and clay content of this unit increases and the unit grades into a sandy loam to sandy clay loam. We interpret this fining-upward sequence as the deposits from a low-energy meandering stream system in which the basal coarse grained deposits are buried by progressively finer overbank and slack-water sediment that fill the abandoned channel and were deposited on the floodplain adjacent to the main channel.

The fluvial deposits are overlain by a series of generally well-sorted, coarse- to fine-grained sands that are sand-blow deposits. The basal contact of the sand-blow deposits is sharp and planar, although locally the erupting sand eroded the pre-earthquake ground surface. The stratigraphy of the sand-blow deposits indicates at least two vigorous eruptions, each of which produced a coarse-grained deposit. The finer-grained sands resulted from sedimentation during lulls in the sand-blow's eruption. The absence of any significant oxidation at the top coarse-grained units is evidence that no significant amount of time transpired between deposition of the successive coarse-grained sand units. Furthermore, the stratification of the fine-sand units is not disturbed or disrupted by bioturbation, which would occur if the vegetation had grown on top of these sand deposits.

Three lines of evidence indicate that the fluvial deposits are late Holocene in age. The trench site is located within a few kilometers of a major recently abandoned channel of the Mississippi River and certainly received significant amounts of sediment during the annual river floods. Furthermore, the very weak soil that is developed in the top of the fluvial deposits indicates that they are late Holocene in age. Lastly, we found artifacts (fragments of pottery) from prehistoric Native American cultures in the fluvial deposits that suggest the fluvial deposits are about 1,200-2,000 years old. Charcoal fragments collected from a hearth in the fluvial deposits are being prepared for radiocarbon dating. Based on the age of the fluvial deposits, and the lack of significant oxidation, mineral alteration, and pedogenesis in the sand-blow deposits (except for the Ap horizon), we believe that the sand blows formed during the 1811-12 earthquakes.

We found no evidence of faulting or brittle deformation that we attribute to tectonic causes in any of the trenches. Major sand-blow dikes were the most prominent structural features in the trenches. The attitude of the dikes ranged from essentially vertical to about 45°, and the strikes of the dikes varied considerably. Some of this variation reflects true changes in the overall strike of
the dikes, but part of the variation results from the sinuosity of the dikes. The strikes of the dikes cluster between about N. 08° W. (352°) and N. 24° E. (024°). Thus, the strikes of the sand-blow dikes are parallel to subparallel to the overall trend of the Bootheel lineament (024°) at this site.

The top of the fluvial deposits was vertically offset across three of the largest dikes, and, in all cases, the downthrown side of the dike is on the east. We found no evidence that these vertical offsets were related to near-surface faulting, and we found no evidence that lateral slip had occurred along these features. Instead, we attribute these vertical offsets to subsidence that resulted from the large volume of sand that was extruded onto the surface from below.

We found no conclusive evidence of near-surface tectonic deformation associated with the Bootheel lineament at this site. The absence of discrete faulting in surficial deposits makes it difficult to directly associate the Bootheel lineament with underlying seismogenic faults, including those that could have slipped during the 1811-12 earthquakes. The geologic evidence from these trenches suggest that, during the past approximately 1,500 years, liquefaction has occurred at this site only during the 1811-12 earthquakes. The extensive liquefaction that did occur here in 1811-12 suggests that site conditions were very favorable for liquefaction. Given the apparent favorable conditions but lack of evidence of prehistoric liquefaction, we conclude that the site has not been subjected to sustained shaking as strong as that which occurred in 1811-12 for at least 1,500 years.

This conclusion is consistent with the findings of paleoliquefaction studies in some parts of the New Madrid seismic zone (Rodbell and Schweig, 1993; Wesnousky and Leffler, 1992), but it contrasts with the findings elsewhere (Schweig and others, 1993). One means of reconciling the apparent contradictory evidence is that multiple seismic source zones are capable of generating large earthquakes in the New Madrid region. This notion is consistent with the occurrence of at least three separate large earthquakes in 1811-12. The paleoliquefaction data that is currently available could be more easily explained by single large events occurring on a discrete source zone in various parts of the NMSZ. It is clear that our present understanding of the distribution and timing of large prehistoric earthquakes in the New Madrid region is incomplete and inadequate to accurately characterize the long-term behavior of the source zones. Additional studies, such as the one we describe here, are needed throughout the region to develop a large enough geologic database to confidently establish the areas affected by individual paleoliquefaction events.

**Crittenden County Trench**

The Crittenden County fault zone (CCFZ) was a primary target for trenching because extensive previous geophysical studies had shown evidence of deformation in very shallow sediments. The fault zone was originally recognized from drill-hole data that showed 78 m of offset at the top of Paleozoic rocks and progressively less offset in shallower stratigraphic horizons. Seismic-reflection data show that the deformation associated with the CCFZ can be traced from the middle crust to within 6-7 m of the surface (Crone, 1992; Luzietti and others, 1992; Williams and others, 1993). Thus, exploratory trenches, which can extend about 3 m below the surface, offered an opportunity to document very shallow deformation associated with a crustal-scale fault zone.

We chose to excavate a trench across the CCFZ in the area between the two drill holes that identified the presence of the fault. The trench site lies within the Holocene-age Mississippi River meander belt, and the surficial deposits are composed almost exclusively of Mississippi River alluvium. Because of the deposits are youthful, the soils in them have moderate to weak horizon development. Thus, pedogenic processes have not obliterated evidence of faulting or deformation in these deposits. The trench averaged 2.5-3 m deep and exposed a sequence of fluvial silts that contained varying amounts of sand and clay. We interpret these deposits as low-energy fluvial sediments that were likely deposited in overbank and slack-water depositional settings. The deposits are conveniently divided into two groups: a lower sequence of silty clay loam, silt loam, loamy sand, fine sand, and an upper sequence of silty clays, silty clay loams, and silty loams.

We found no evidence of faulting in the trench. The most significant structural feature was an unconformity that separated the two depositional sequences. The unconformity progressively rose toward the western end of the trench, and stratigraphic units in the upper sequence pinched-out against the unconformity or thinned greatly to the west as the unconformity became shallower.
This unconformity indicates the presence of a buried feature that had about 1.2 m of topographic relief at the time that the upper sequence of sediments were deposited.

Data from the trench do not yield conclusive evidence about the origin of this buried topographic feature. Much of the present landscape in Crittenden County is the product of fluvial processes, and river channels with several meters of relief are common. Thus, in the absence of evidence of faulting or other tectonic causes, it is reasonable to attribute the relief to fluvial processes. However, the coincidence of the buried feature with the shallow subsurface deformation imaged in the high-resolution reflection data suggests that the buried topography could be related to tectonism (Williams and others, 1993). Because Holocene age sediments are involved in the deformation, determining the origin of the buried feature is important for earthquake hazard assessments.

(Dart & Swolfs) The principal objective of this research was to interpret the available geological and geophysical subsurface data in the area of abundant seismicity in order to identify fault-related features and to evaluate their tectonic significance. The comprehensive subsurface database (Dart, 1992) has led to construction of a detailed structure contour map of Precambrian basement and interpretative cross sections of the Reelfoot rift. From these maps and sections, we have identified intra-rift structures that we interpret as half grabens and accommodation zones. Linked half grabens apparently form two full graben basins within the rift; the basins are separated by trans-rift high-relief accommodation zones (Rosendahl, 1987). The zigzag pattern of NMSZ seismicity is inferred to be associated with specific northeast- and northwest-trending seismogenic half-graben structures. The sense of displacement on these left-stepping, northeast-trending seismogenic structures is right-lateral (Russ, 1982; Gomberg, 1992). We infer that these northeast-trending structures are interconnected with seismogenic northwest-trending structures and that the sense of displacement on these northwest-trending structures is left-lateral (Clendenin, 1991). Some anomalous geomorphic features in the northern Mississippi Embayment may be associated with recent surface deformation, for example, sand blows (McKeown, 1982), the Lake County uplift, Reelfoot Lake, and the St. Francis sunk lands (Russ, 1982; Gomberg, 1992), the sinuosity of the Mississippi River near Caruthersville, Missouri (Fischer and Schumm, 1992), and the drainage pattern of the White River in northeastern Arkansas (Mayer, 1993). We relate these deformational features with lateral displacement along the strikes of these intersecting northwest-trending and northeast-trending, left-stepping seismogenic structures and with subsidence and uplift at their intersections. We also found that the meander belt of the Mississippi River and the axis of the Mississippi embayment syncline south of New Madrid, Missouri appear to be influenced by (and perhaps controlled by) the areas of uplift at the intersection of faults in the underlying Reelfoot rift.

(Diehl) Fractures associated with a dilational jog in the English Hill fault were conduits for migrating fluids. The fractures are now filled with multiple generations of calcite, saddle dolomite, and a hydrocarbon residue. Carbonate-filled veins record information about the deformational history of the fault, and cathodoluminescence studies clearly reveal at least 6 different stages of carbonate-fluid influx. Early calcite precipitates have micritic textures and inclusions, and, in general, early phases are non- to darkly luminescent, which indicates that they are iron-rich. Late-stage calcite phases are sparry and limpid with dull to bright luminescence. These textures and luminescence properties record changes in the fluid chemistry that probably correspond to progressively less saline conditions.

Rip-out wall-rock clasts are microscopic kinematic indicators. The clasts are stretched and thinned and occur in evenly spaced, wall-parallel bands. These bands of sigmoidally deformed clasts suggest a record of successive opening along the vein wall, and the sigmoidal deformation indicates a right-lateral sense of displacement along this segment of the English Hill fault.

The density of veins increases towards the fault zone, which may indicate an increase in the amount of strain. This increase in strain results in a high degree of wall-rock fracturing and can create low-pressure fracture zones that invite fluid influx. In addition, strain incompatibilities at fault bends can produce fluid flux (Pavlis and others, 1993), and, at Grays Point, this relation is indicated by the successive filling of veins.
The succession of minerals in the carbonate-filled veins records cycles of build-up and release of fluid pressure. This cyclic nature of fluid pressure is a consequence of adjustments in the English Hills fault system to minimize the strain incompatibilities at the dilational jog during repeated periods of earthquake activity.

The quantity of cuttings for many old drill holes in the New Madrid region is so small that the amount of sample to work with is very limited. Drill-cutting samples from continuous footage in the Strake and Killam drill holes were combined to obtain the quantity of minerals needed for potassium-argon dating. Separation of the biotite and amphibole were difficult because both minerals have a similar density and both are iron-rich. Because biotite and amphibole have different closure temperatures, dating both minerals provides a check on the date of the rock. Hand-picking of the final separations is currently underway. Frank McKeown (USGS Volunteer) will be assisting in this final process. Larry Snee (Branch of Geochemistry, Denver) will begin dating the samples in late January or February, 1994.

REFERENCES CITED


REPORTS


Earthquake Hazard Research
in the Pacific Northwest using Washington Regional Seismograph Network data

14-08-0001-G1803
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October 1, 1992 - September 30, 1993

Investigations

This research focuses on earthquake hazards in the Pacific Northwest, including large scale plate interactions, through the study of regional structure and tectonics. Investigations by our research group include a project to interpret crustal velocity structure across the Cascade range using travel times from reflected and refracted earthquake rays, an investigation of P-wave multiples arising from teleseismic arrivals reflected from the subducting plate, and an investigation of the Scott's Mills earthquake in northern Oregon. We are also completing articles on using coda amplitudes to determine source scaling and estimate earthquake moment, and on subduction kinematics of the subducting plate.

East-west cross-Cascades velocity structure profile

An M.S. thesis by Andreas Schultz entitled "A 2-D Velocity Structure for a Cross-Cascades Profile Using Earthquake Sources with Application of Reflectivity Synthetic Modeling" was completed in this contract period. The aim of this study was to develop a 2-D velocity model across the Cascade Range of Washington state, connecting the structure of the Columbia Plateau with that of the Puget Sound. By using PmP (Moho reflections) as well as Pn (headwaves) from earthquake sources along the profile, we were able to place constraints on both the dip and depth of the continental Moho between Bremerton and Walla-Walla, Washington.

The final model has a continental Moho which dips to the east beneath the Puget Sound, and to the west in eastern Washington; consistent with a root beneath the Cascade core. The maximum crustal thickness under the high Cascades was 47 km, shallowing to 34 km in eastern Washington and to 35.5 km under the Puget Sound. Thus the Cascade Range has a approximately 12 km deep "root" in this area.

Crustal and upper mantle structure beneath Washington state from array analysis of short-period network data

Since 1980 digital data have been recorded by the WRSN, including over 5,000 teleseisms. This wealth of data, although limited by vertical component, short-period instrumentation, should provide a sufficient number of waveforms such that small amplitude phases generated by near-receiver structure can be enhanced and identified.

We are adopting an approach similar to source-equalized P-wave receiver function analysis. However, we estimate the source-time function, near-source structure, and common-path effects for a given event by stacking all stations with signals meeting some minimum quality criteria. The resulting stack, which represents common source and path effects, is deconvolved from each individual seismogram to obtain structural information associated with each site. In particular, we are seeking to use P-wave multiples to constrain the depth to reflecting interfaces at crustal and upper mantle depths. Signal-to-noise ratios for each station are improved by slant-stacking deconvolved seismograms in 20° back-azimuth increments. Preliminary results from two stations on the Olympic Peninsula are consistent with a subducted oceanic slab dipping east or southeast.
Investigation of Scotts Mills, Oregon Earthquake

On 25 March 1993, a magnitude 5.6 earthquake occurred in the crust near Scotts Mills, Oregon. The event was widely felt in western Oregon, including Portland and Salem, and caused some damage. For about a week following the mainshock, the USGS and other investigators operated portable seismograph stations with high dynamic range to record aftershocks.

We have combined the trace data from the portable USGS stations with data from the WRSN to create a high-quality master seismogram data set for aftershocks from this earthquake. Preliminary analysis of these data indicates that the aftershocks lie on a fault plane striking west-northwest and dipping about 60 degrees to the northeast. The mainshock exhibited oblique reverse or thrust motion in response to north-south tectonic stress in the crust. The motion and stress are consistent with other crustal earthquakes in western Washington, although we have few such observations in western Oregon.

The agreement of the fault plane parameters with the previously mapped Mt. Angel fault system suggests that this type of crustal earthquake could occur elsewhere in western Oregon on this or other similar northwest trending fault zones such as the Portland Hills fault zone. Study of this earthquake will help in further assessing crustal earthquake hazards in western Oregon and western Washington.

Articles

Chiao, L.-Y., and K. C. Creager (in preparation) Geometry and lateral membrane rate of the subducting Cascadia slab, to be submitted to JGR
Dewberry, S.R. and R.S. Crosson, (in preparation), Source scaling and moment estimation for the Washington Regional Seismograph Network using coda amplitudes, to be submitted to BSSA.
Mundal, I., M. Ukawa, and R.S. Crosson, (in preparation), Normal and anomalous P phases from local earthquakes, and slab structure of the Cascadia Subduction zone, BSSA
VanDecar, J.C., R.S. Crosson and K.C. Creager, (in preparation), Travel-time inversion for subduction zone structure: I. The effect of three-dimensional ray tracing on resolution analysis, to be submitted to JGR.

Theses


Abstracts

Investigations

Nine high-quality reflection seismic lines of the offshore are presently being integrated with geologic data from oil exploration wells and various seafloor geologic maps (Figure 1). Structural interpretations of a number of the lines are now complete and it is expected that the remaining lines will be interpreted by the end of 1993. Several retrodeformable cross sections will then be made along the northern portions of the lines which cross the Santa Monica basin and southern limb of the Santa Monica Mountains anticlinorium. Specific goals will be to identify areas of Pliocene and Quaternary convergence, delineate the structural geometry of these structures, and determine convergence rates.

Results

1. West of the city of Santa Monica the south limb of the Santa Monica Mountains anticlinorium extends several kilometers southward under Santa Monica Bay. Pliocene and Quaternary strata along the limb are clearly syntectonic and form a south-vergent growth-wedge. Much of the Elysian Park thrust system is blind and only a small fraction of the thrust slip reaches the seafloor in a very complex system of small reverse faults and folds distributed over a several kilometer wide zone.

2. In the northeastern portion of the Santa Monica basin an east-west trending zone of Quaternary folds, 15-20 km wide, lies southward of the Santa Monica Mountains anticlinorium. The presence of these structures supports Hauksson and Saldivar's (1989) thesis that seismically active north-south convergence associated with the Transverse Range extends across much of the Santa Monica basin.

3. Preliminary interpretations of the regional seismic lines that extend south of the Santa Monica basin show that many of the northwest trending ridges of the continental borderland record significant amounts of Pliocene and Quaternary convergence. These structures are generally anticlinal and are analogous to northwest trending convergent zones in the onshore Los Angeles basin such as the Puente Hills, Palos Verdes Hills, and Torrance-Wilmington anticline.

References

Figure 1. Locations of offshore seismic reflection lines used in present study. Onshore cross sections lines are from previous NEHRP research by authors.
Reanalysis of Instrumentally Recorded United States Earthquakes

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Investigations

1. Describe the seismicity following the $M_w$ 8.7, 1957 Aleutian arc earthquake to better understand the earthquake cycle in subduction zones. This major undertaking also will answer numerous questions concerning the size and probable rupture characteristics of this important earthquake (William Spence with extra-project colleagues T. Boyd and E.R. Engdahl).

2. Interpret the seismicity before and after the $M_s$ 7.8, 1974 Peru earthquake to clarify the nature of subduction at this complex convergence zone (William Spence with extra-project colleague C.J. Langer).

3. Quantify the compressional stress seaward of the asperity that controlled the $M_S$, 1985 Valparaiso, Chile, earthquake, and quantify the compressional stress seaward of the Shumagin seismic gap in the Aleutian arc (S. Mueller and W. Spence with extra-project colleague G. Choy).

Results

1. Seismicity along the Aleutian arc has been cataloged and relocated. The time period covered by the event catalog includes the aftershock sequences of the great 1957 Aleutian Islands earthquake and the 1986 Andreanof Islands earthquake. Both events ruptured a 250 km-long portion of the central Aleutian Arc. Relocations are based on P-wave arrival times published in the ISS, BCIS, and ISC Bulletins and include corrections for near-source velocity structure associated with the downgoing slab. Magnitude estimates are also extracted from the bulletins, when available, or are estimated from microfilmed records. Over the time period covered by our catalog, 1957 through 1989, the level of completeness is down to a magnitude of 5.5. From 1964 through 1989, the level of completeness is 4.7.
The locations of earthquakes occurring along the central Aleutian arc indicate that aftershocks of the 1957 and 1986 earthquakes are spatially anticorrelated. The aftershock distribution of each event is interpreted as being indicative of the distribution of the respective seismic moments. Thus, the moment distribution of the 1986 earthquake is anticorrelated with that of the 1957 earthquake. This observation suggests mechanically strong portions of a fault (asperities) cannot be identified by simply mapping the moment distribution of the most recent great earthquake. It also suggests that a fundamental tenant of the asperity model, that rupture always occurs on the strongest portion of the fault with weaker portions rupturing either aseismically or dynamically as a result of rupture on a strong fault patch, may be wrong. Thus, observing the moment distribution from earthquakes occurring during the present cycle may tell us little about what the distribution of moment release will look like for the next earthquake in the cycle.

2. The aftershocks of the October 3, 1974, Mw 8.1 earthquake have been relocated using data from a rapidly installed, 11-station temporary seismic network. These remain among the best-observed aftershocks of all circum-Pacific subduction earthquakes. Recent modelings of the rupture history of the main shock, done in other studies, indicate rupture on the thrust interface updip to the Peru-Chile Trench and bilaterally. Aftershocks, including a Ms 7.1 event, primarily are near the downdip periphery of the main shock’s shallow-dipping thrust surface. For a group of aftershocks further downdip, a composite focal mechanism shows right-lateral, strike-slip displacement. This is consistent with moment release in the deeper zone corresponding to the predominant moment release of the main shock being north of the strike-slip deformation. The overall main shock rupture and aftershock characteristics may be related to the broad influence of the Nazca Ridge. Preseismicity was concentrated at the downdip edge of the main shock rupture and also in the steeper plate section, consistent with the main shock’s asperities being loaded by sinking of the Nazca plate. The space-time history of the aftershocks shows an interplay between a cluster in the steeply dipping zone and a shallower cluster near the Nov. 9, 1974, Ms 7.1 aftershock, also reflecting loading of that aftershock’s asperity by continued sinking of the Nazca plate. At a depth of about 20 km, the 11°E-dipping Nazca plate increases in dip to 30°E; this hinge is directly beneath the rapidly subsiding Lima Basin. Although an episode of plate motion must have bridged both this hinge and the Peru-Chile trench during our monitoring period, the corresponding bending episodes essentially were aseismic.

3. It is demonstrated that a thrust outer-rise earthquake that occurred on October 16, 1981 near Valparaiso, Chile, resulted from stress concentrations induced by a subduction-zone asperity which subsequently ruptured during the subduction earthquake that occurred on March 3, 1985. The net force resulting from these stress concentrations is determined to exceed available plate-driving forces by an order of magnitude and was therefore the dominant mechanism promoting rupture of the subduction-zone asperity. This confirms previous speculation (Christensen and Ruff, 1988) that the outer-rise event was a manifestation of the

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high seismic potential for the larger subduction event. In contrast to the 1981 event, the majority of thrust outer-rise events are not followed by subduction earthquakes. Lithospheric unbending (i.e., decreasing plate curvature) within the outer trench wall may be responsible for some of these events, an explanation that requires neither excess inplane compression nor earthquake generation in response to ductile creep. Finally, previous interpretations of outer-rise seismicity, which have assumed elastic superposition of flexural and inplane stress, are shown to be possibly incorrect.

Reports


Integrated Approach to Earthquake Hazard Assessment of a Subduction Segment: 
A Case Study of the Shumagin Islands Region, Alaska (grant 1434-93-G-2325)

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Investigations:

Stress transfers during the earthquake cycle in a subduction segment with a row of asperities have been studied, with the use of a 3D finite element model. The model is a new tool in the framework of the integrated approach, based on seismicity and deformation data, to earthquake hazard assessment of a subduction segment that we have previously developed based on 2D viscoelastic modeling. Preliminary inferences of the use of such a model for the interpretation of geodetic records (strains, tilts, uplift) in the Shumagin Islands region, Alaska, are discussed.

Results:

We have added a new tool to our past set of techniques in the assessment of earthquake hazard in a subduction segment. In the past we have used a 2D finite element model of such a segment (a case study of the Shumagins: Dmowska et al., 1992, Zheng et al., 1992) that included two elastic plates with the proper geometry, the interplate interface locked at all times except the earthquakes themselves, and viscoelastic mantle. We have run earthquake cycles in such a model and compared the resulting stressing/deformation with the time/space dependent geodetic observations from the surface. However, dealing with a 2D simplification we were not able to address the inhomogeneities along strike in locking properties of the interplate interface (e.g., large asperities) and resulting inhomogeneities in stressing/deformation patterns as observed on the surface. To improve that situation we have developed a 3D finite element model that allows for the presence of a row of asperities along the interplate interface, and otherwise is similar to the 2D model. Our first results were presented in Dmowska et al., 1993 and Zheng et al., 1993, and are briefly described below.

We analyze space- and time-dependent deformation associated with earthquake cycles in a 3D finite element model of a subduction segment with a row of asperities. Both the subducting and upper plates are elastic and the surrounding mantle is viscoelastic. The segment considered is repeated periodically along the convergent margin and the interplate interface in each segment has 1 or 2 asperities, which are highly coupled areas surrounded by either freely slipping or viscously relaxing fault zones. The slip in earthquake cycles is prescribed along the otherwise locked asperities. Resulting deformation reflects the cycle-related changes caused by identically repeated subduction events.

With fixed dip of 25°, as well as fixed plate thicknesses and 1 asperity per segment in our basic model, we analyze the dependence of resulting deformation on different fault (freely slipping or stiff), mantle viscosity, and upper plate stiffness parameters. We repeat this analysis for the
case of 2 asperities in each subduction segment.

We show results for the space- and time-dependent deformation of the top of the upper plate, which might in some cases be accessible for geodetic measurements, as well as the area of the outer-rise, with its sometimes pronounced cycle-related seismicity. In particular, we observe the important influence of the presence of asperities on the cycle-related stressing and deformation. Figure 1a shows a single asperity along the thrust interface and Figures 1b and c show two cases of pairs of asperities. Figures 2a,b,c show contour plots of the corresponding changes in surface extensional strain in directions perpendicular to the trench immediately after imposing slip on the asperity(ies). Figure 3 shows that surface strain as a function of time and position along strike for the row of elements darkened in the insert. All results shown here are for the case in which the remainder of the thrust interface, outside the asperity(ies), is allowed to freely slip.

There is strong enhancement of the cycle-related deformation in the area of the upper plate positioned over the asperity. The size and shape of the influenced area is affected obviously by the size of the asperity, but also by the mechanical behavior of the fault zone surrounding the asperity. These model results are meaningful for interpretation of geodetic data along profiles perpendicular to the trench, and show clear differences depending on where a particular profile is positioned in relation to the underlying asperity.

For the outer-rise area there is space- and time-dependence of cycle-related stressing due to the presence of asperities. This is consistent with past seismological observations (Dmowska and Lovison, 1992) that seismicity clusters along the subducting margin in association with asperities.

For the Shumagin Islands segment the matching of our 2D model results with the geodetic measurements (strains, tilts, uplift) from the Islands network requires that the average seismic coupling factor along the interplate interface (without asperities) would be rather low, equal to 0.1 (Dmowska et al., 1992). As our 3D modeling shows, similar fit would be achieved if, instead, the Shumagin segment were positioned in a corridor between two larger asperities, e.g., one to the east, where the 1938 earthquake nucleated, and one to the west, in the western part of the Shumagin Gap area (which shows higher coupling, as revealed by larger outer-rise as well as down-dip earthquakes, Dmowska et al., 1992).

Reports:


Zheng, G., R. Dmowska and J. R. Rice, "Deformation during the earthquake cycle in an oblique

Figure 1. The thrust interface (vertical axis is distance in km from the trench, measured negative down-dip; horizontal axis is distance in km along strike). Case (a) is for a single asperity and cases (b) and (c) are for pairs of asperities. Periodic boundary conditions apply at the ends along strike. Slip is imposed on the asperities and calculated elsewhere on the thrust interface according to an assumed rheological law, taken as freely slipping in cases shown here.
Figure 2. Contour plots of the change in trench-perpendicular extensional strain $\varepsilon_{11}$ along the surface of the earth, immediately following slip on the asperity or asperities, for the three cases shown in Figure 1. Now the positive range on the vertical axis gives distance from the trench, in km, on the overriding plate; horizontal axes give distance along strike. The dip angle has been taken as $25^\circ$ here and the thrust interface outside the asperities allowed to freely slip in response to the imposed motion and deformation of surrounding material.
Variation of Strain $\varepsilon_{11}$ (unit: $\varepsilon L/\alpha TV$, $L=80$ km, $\alpha TV =$ seismic slip)

$\varepsilon_{\text{max}} = 0.97E-1$  $\varepsilon_{\text{min}} = -0.84E-1$

Figure 3. The inset diagram shows a section through the mesh, perpendicular to the trench, and a particular row of elements at the surface is darkened. The wireline plot shows the trench-perpendicular extensional strain $\varepsilon_{11}$ as a function of distance along strike through that element row and of time through one complete earthquake cycle. This is for case (a), a single asperity, and for a freely slipping interface outside the locked asperity.
Source Characteristics of Events in the San Francisco Bay Region

Contract No. 1434-93-G2311

Program Element II.2

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INVESTIGATIONS

The objectives of this project were several fold. First, a time domain moment tensor inverse formalism was developed to allow routine estimation of the moment tensor of events occurring in the greater San Francisco Bay area, as well as throughout central and northern California. Second, broadband waveforms recorded by the Berkeley Digital Seismic Network (BDSN) were forward modeled to calibrate velocity models for use in the moment tensor inversion, as well as to better understand regional velocity structure, and wave propagation. Effort was also expended to calibrate models for the study of significant historic seismicity. The method, and velocity models are undergoing additional refinement so as to develop a near-realtime capability.

RESULTS

Moment Tensor Method

We have developed a moment tensor inverse method to study the source parameters of earthquakes in the greater San Francisco Bay Area, as well as throughout central and northern California. The method is essentially an extension of Dreger and Helmberger's (1993) method, in which three-component bodywaves, and in some cases the entire waveforms including surface waves are utilized. We assume that the isotropic component of the tensor is zero and the point-source approximation is sufficient. Source depth is not directly solved for but is estimated iteratively by finding the value which gives the greatest variance reduction.

With this program we have developed the capability to routinely estimate the moment tensors of earthquakes ranging in size from $M_w 3.5$ to more than $M_w 6.0$ using local and regionally recorded three-component seismograms. The lower limit of the method depends upon the signal-to-noise levels and the number of available stations. Single station data are often sufficient. The upper limit depends upon the appropriateness of the point-source assumption. In addition, we are finding that a rather simple regionalization of California velocity structure based on average crustal thickness and velocity is adequate for the retrieval of the moment tensor, though additional refinement and calibration are needed.
Figure 1 shows the solutions we obtained for a number of the larger events that have occurred throughout central and northern California during the period from 1991 to May 1993.

**Velocity Model Calibration**

The central coast ranges are structurally very heterogeneous, and the P-wave velocity models used by the USGS to locate earthquakes in this region, derived from various studies, reflect this. Figure 2a compares several S-wave models derived from the CALNET P-wave models assuming that Poisson’s ratio is 0.25. All of the models show that the average crustal thickness in the central coast ranges is 25 to 27 km. The near-surface velocities in the models vary considerably, while the mid-crustal velocities are more uniform. The crustal thickness in the Sierra Nevada is on average 35 km, and shallow and mid-crustal velocities are 0.5 to 1 km/s faster than in the coast ranges (Figure 2b).

**Central Coast Ranges.** Broadband seismograms recorded by the BDSN station BKS for the 920919 and 930116 events show the influence of the heterogeneous near-surface velocity structure (Figure 3). The distances of both events to the BKS station are nearly the same, but from opposite azimuths. The level of Love wave dispersion is very different for the two paths, where the path from Gilroy is more dispersed due to a greater interaction with the shallow quaternary sediments of the San Francisco bay area. The body waves were found to be relatively complex and dominated by two large pulses that were identified as SmS (Moho reflection) and sScS (reflection from a lower crust interface at approximately 17 km depth) by forward modeling with Generalized Ray and FK integration synthetic seismograms. The relative timing and amplitude of these phases in the data for the two events reflect significant differences in source depth, where the Geysers earthquake ruptured at a depth of 2 km and the Gilroy earthquake at a depth of 7 km. Two velocity models were developed, one for each event (path), and are plotted as solid lines on Figure 2a. Note that these models mark the extrema in near-surface velocity of the USGS, CALNET models.

Filtered cross-correlation functions were used to evaluate the fit of the synthetics to the data in a broadband sense as well as to evaluate a suitable bandwidth for use in the moment tensor inversion. For example, Figure 4a compares the broadband (0.01 to 1 Hz) tangential component displacements recorded at BKS for the Gilroy earthquake with synthetics computed with the SoCal model (Dreger, 1992; Dreger and Helmberger, 1993), GIL7 (developed for this path), MTM (developed for the Geysers path), and HAY (USGS, Calnet model). Table 1 lists the models. There are clearly significant differences in the development of surface waves for each of the models. The surface waves are influenced strongly by the shallow velocity structure. The absolute and relative amplitudes and timing of body wave phases are strongly dependent on the depth of lower crustal interfaces and the Moho discontinuity, as well as the near-surface velocity gradient.

Figure 4b compares cross-correlation functions of the data and the four velocity models. Only model GIL7 fits the Gilroy data in a broadband sense (0.01 to 1.0 Hz). At longer periods the fits of the other models improve, and below 0.1 Hz the GIL7, MTM, and HAY models are found to perform very well. An inversion of synthetic data (computed with model GIL7) using HAY model Green’s functions was performed to test what the potential
bias in a given solution might be due to using an incorrect, simplified velocity model. The results of this test revealed that at periods longer than 10 seconds the resulting errors were less than 10°. The GIL7 model has been tested for events both south (events 1 and 14; Figure 1) and north (events 2, 3, 4, and 5; Figure 1) of the San Francisco Bay Area and has been found to perform quite well. Solutions for these events were found to agree with those obtained from first-motion polarities, regional surface waves, and Harvard CMT results (Table 2). Figure 1 shows the area in which the GIL7 model has been found to be suitable for source analysis.

Sierra Nevada. The May 17, 1993 Eureka valley earthquake ($M_w=6.1$) offered the most difficult test of this methodology to date. This event was located on the eastern border of California, between the dense CALNET array of northern and central California, and the Southern California Seismic Network (SCSN) of southern California. The remoteness of the event has made obtaining reliable first-motion mechanisms, and source depth estimates nearly impossible. The earthquake was well recorded by BDSN and TERRAscope with excellent signal-to-noise ratios allowing the various regional waveform inversion methods to be used and the resulting solutions compared.

One of the problems the location of the earthquake posed to the methodology described in this report, was that paths to the west crossed several significant geologic provinces. For example, the path to MHC crossed the Sierra Nevada, San Joaquin valley and the Coast Ranges domains. Preliminary moment tensor estimates using filter corners of 0.01 0.1 Hz proved to be unstable. Using filter corners of 0.01 to 0.05 Hz improved the stability significantly, however single station inversions remained relatively unstable. Fortunately, the broadband networks of California, at the time of this event, have developed to the point where even in this remote location good azimuthal coverage is available. Figure 5 compares the three-component, band-pass filtered (0.01 to 0.05 Hz) data and best fitting synthetic seismograms. The complete waveforms were used in the inversion, and the SoCal model was assumed for each path. The shaded fault plane solutions were computed by single station inversion, while the unshaded solution is the simultaneous, five station result given in Table 2. Note that four of the stations (PAS, GSC, MHC, and NEE) give very good single station results, while station CMB does not. There is clearly a problem in the rotation of the CMB data and it appears that there are significant, multipathed, long-period P-waves affecting the single station results. This is probably due to a large lateral change in crustal velocity along the eastern front of the Sierra Nevada. Similarly the S-wave would be expected to be affected by such a contrast in velocity. In fact, in the five station inversion the synthetic S-waves at CMB are found have reversed polarity. The results from this event, as well as those from several other earthquakes in the Sierra Nevada region (Figure 1) indicate that the SoCal velocity model is suitable in this region for source analysis.

San Francisco Seismicity. Since January 1, 1993 there have been three events with magnitudes greater than 4.0 in the greater San Francisco Bay Area (event nos. 12, 19, and 22; Table 2). These events all occurred on the east bay, Calaveras and Hayward fault systems. On September 19, 1993 two small events ($M_w3.5$) occurred in the northern San Pablo bay at the terminus of the Hayward fault and juncture with the Rodgers Creek fault system. We have computed moment tensors for all of these events and compared the
results with first-motion polarities (David Oppenheimer, written communication, 1993) and regional surface waves (Mike Pasyanos, written communication, 1993) on Table 2. Generally, all of the solutions are predominantly right-lateral strike slip on northwest trending, steeply dipping planes. The two events at the northern San Pablo Bay show somewhat shallower dips (approximately 60° to 70°). The epicentral locations of the events plot on the northern terminus of the Hayward fault, but the dip of the planes together with the depths of the events indicate that the west-dipping Rodgers Creek fault system is the causative structure (Pat Williams, personal communication, 1993).

CITED REFERENCES


REPORTS


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α and β are the P- and S-wave velocities in km/s and ρ is density in g/cc. Z is the depth to the top of the interface. The S-wave velocities for model HAY were computed assuming Poisson's rationship where $\alpha = \sqrt{3}\beta$. 

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+ indicates the source depth was restrained
* indicates either no convergence or non-unique results

Key to methods:
(1) Body waveform Moment tensor inversion (Mag. is Mw)
(2) USGS first motion mechanism from UCB Data Center (Mag. is duration magnitude)
(3) Regional surface wave inversion (Mag. is Mw)
Figure 1. The locations of the BDSN Network (triangles), and TERRAscope stations (squares) are plotted with the earthquakes for which moment tensors have been computed (stars). The focal mechanisms show the best double couple solutions determined by decomposition of the moment tensor. Table 2 lists the solutions and compares them with those obtained by other methodologies. The dashed lines show the demarcation of the velocity model domains that are used in the inversion.

Figure 2. Compares USGS crustal models (dashed) for the (a) Coast Ranges and (b) Sierra Nevada. The S-wave velocities were derived from the P-wave models assuming Poisson's relationship ($\alpha = \sqrt{3}\beta$). The solid lines show the MTM and GIL7 models for the Coast Ranges and the SoCal model tested for the Sierra Nevada. Table 1 lists the velocity models.
Figure 3. Comparison of tangential data (solid) and synthetics (dashed) for the 920919 Geysers and 930116 Gilroy earthquakes recorded at BKS (distances of 119 km and 117 km, respectively). The Geysers and Gilroy synthetics were computed with the MTM and GIL7 velocity models (Table 1), respectively. The source parameters listed on Table 2 were used, and a triangular source time function of 0.8 seconds duration was assumed.
Figure 4. (a) Tangential component displacement data for the 930116 Gilroy earthquake are compared with SoCal, GIL7, and HAY synthetics. The source parameters on Table 2, and a triangular source time function with a duration of 0.8 seconds were used to construct the synthetic seismograms. (b) The tangential component displacement data recorded at BKS for the 930116 Gilroy earthquake are cross-correlated with synthetics computed with the GIL7, MTM, HAY and SoCal (SC) velocity models in several frequency bands. The fit to the data is noticeably improved at frequencies less than 0.1 Hz. The GIL7 model fits the data well in a broadband sense (0.01 to 1.0 Hz).
Figure 5. Single station solutions (shaded) are compared with the solution obtained by simultaneous inversion of all five stations (unshaded, Table 2) for the 930517 Eureka Valley earthquake ($M_w$6.1). Both the data and synthetics were band-pass filtered with corners of 0.01 and 0.05 Hz. The synthetics plotted on this figure were computed with the single station solutions. Note that the waveform fits are quite good at PAS, GSC, MHC and NEE, and that the path to the MHC station crosses the Sierra Nevada, San Joaquin valley and Coast Range domains. Since the path is perpendicular to the regional north-northwest structural trend, there is minimal waveform distortion. In contrast, the path to CMB crosses into the Sierra Nevada at relatively low angle and there are clearly multipathed, long-period P-waves evident in the tangential component data.
A New Madrid Seismic Zone Paleoearthquake Study:  
The Magnitudes and Timing of the Towosahgy Events

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Investigations

The purpose of this research was to determine the timing and magnitude of 
the Towosahgy paleoearthquakes primarily through the determination of the 
areal extent of the associated paleoliquefaction deposits. This involves the 
careful examination of the liquefaction deposits and an ability of 
distinguishing them from (primarily) the younger and more extensive 1811 - 
1812 deposits.

Field investigations during FY92 included interpretation of aerial 
photographs and infrared images and a field survey of approximately 2000 
square kilometers around Towosahgy and areas to the south. Eight sites have 
been excavated and samples have been collected for both $^{14}$C and 
thermoluminescence analysis.

Results

We have found at least one site (WD102-1) that yields convincing pre-1811-12 
liquefaction deposits (Fig. 1). WD102-1 is approximately 20 km northeast of 
New Madrid, MO, on the east side of Wilkerson Ditch (Fig. 2). Numerous 
northwest-striking sand dikes feed two separate horizontal sand deposits, 
each of which is capped by a well developed soil.

The upper sand blow deposit is capped by a 10 cm-thick soil A-horizon and is 
fed by a near-vertical sand dike that cross cuts the lower sand blow deposit.  
An age-estimate of a sample of wood buried by the higher sand suggests that 
the deposit formed in response to the 1811-1812 earthquakes.

The lower sand blow deposit is topped by a 28 cm-thick soil A-horizon. We 
have not been able to establish a measure of the absolute age of this deposit, 
but the well-developed soil suggests that it is significantly older than the 1811-
1812 deposit. That is, it appears very unlikely that this deposit can represent 
one of the three 1811-1812 deposits.
Future Work

Further work will concentrate around the WD102-1 site as well as further afield. We are also examining liquefaction events in areas where artifacts from native Americans have been found, since these archeological deposits are proving very useful farther south (see report by E. S. Schweig, III).

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Figure 1: Simplified log of the trench wall at site WD102-1. The relative ages of the two sand blow deposits are clearly shown by the thin sand feeder dike that cuts across the lower (older) sand deposit. Note that each sand deposit is capped by a relatively well-developed soil A-horizon.
Figure 2: Location of Trench WD102-1 (WD) relative to Towosahgy (T) and the current distribution of seismicity.
Seismic Studies of Fault Mechanics

9930-02101

William L. Ellsworth
Alex Cole and Lynn Dietz

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345 Middlefield Road - MS 977
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415-329-4784

Investigations

1. Temporal variations in wave propagation associated with the 1989 Loma Prieta earthquake.
2. Rupture variation in numerous cycles of a recurrent small earthquake.
3. Analysis of recent Parkfield seismicity in relation to the 1966 foreshock and mainshock.
4. Prototype rapid earthquake notification system (Earthworm) for the San Francisco Bay Area.

Results

1. The Loma Prieta earthquake occurred in a densely instrumented region with a history of microearthquake recording beginning more than a decade before the October, 1989 mainshock. This affords an unprecedented opportunity to detect changes in seismic wave propagation in the Earth’s crust associated with a major earthquake. In this study we used pairs of nearly identical earthquakes (doublets) to search for temporal changes of coda attenuation in the vicinity of the Loma Prieta, California earthquake. The high coherency of waveforms for the doublets make them an ideal tool for searching for changes in seismic wave amplitude. By forming the spectral ratio of short windows of seismogram for each station observing the doublet, we can measure amplitudes with a precision of about 10% over a 1 Hz bandwidth from 1-15 Hz. Multiple samples of each pair of seismograms, obtained by moving the analysis window along the trace from the S-wave arrival into the coda, permit us to determine the change in coda-Q in multiple frequency bands and with a precision of about 5%. This method provides an estimate of changes in coda-Q that is insensitive to other factors that influence coda amplitudes.

We analyzed 21 doublets recorded from 1979 to 1990 that span the pre-seismic, co-seismic, and post-seismic intervals. Our observations place an upper bound on pre-seismic, co-seismic, and post-seismic changes of coda-Q in the epicentral region of the Loma Prieta earthquake of about 10 percent. Even at this low level, the changes are neither spatially coherent nor coherent in frequency. This is in sharp contrast to other studies that have reported much larger precursory changes in coda-Q for other earthquakes.

2. We studied eighteen nearly identical magnitude 1.5 earthquakes which occurred on the Calaveras fault between 1980 and 1991 at time intervals ranging from a few days to several years (figure 1). Their locations, estimated by waveform cross-correlation, all lie...
within 20 meters of each other. The events with the longest recurrence interval, the time since the previous earthquake, tend to have about 20% larger seismic moment than those with the shortest intervals. The observed increase in moment may provide an empirical basis for theoretical models that predict increasing stress drop with increasing recurrence interval due to increasing contact area on the fault plane. In addition, the rupture durations of the events with the longest recurrence intervals are more than a factor of two shorter than for the events with the shortest intervals. Laboratory experiments have shown that the rupture process slows with the presence of fault gouge and slows with increased fault surface roughness. Therefore decreased duration, as well as increased friction, may result from fault healing due to longer stationary contact time.

3. We have located the hypocenter of the 1966 Parkfield, California, earthquake and its foreshock relative to two recent, nearby events by applying the method of joint hypocentral determination (JHD) to P-wave arrival times reported by 18 common stations at epicentral distances from 20 to almost 500 km. The main shock has nearly the same epicentral coordinates as earlier locations at 35°57.25'N, 120°29.84'W (±0.5 km), but the depth is greater at 9.9 km (±0.8 km). The foreshock locates 1.2 km to the northwest of the main shock and at 1 km shallower depth, although this position is not precisely determined. The revised hypocentral depths place the nucleation zone for the earthquake significantly closer to the base of microearthquake activity recorded since 1975 than previously believed. Both 1966 hypocenters locate within seismically inactive regions of the fault plane and are generally enclosed by recent activity (figure 2). JHD relocation of all six nearby M>4 events from 1967 through May 1993 shows that all but one locate over 2 km from the either the 1966 main shock or foreshock. The M 4.4 event of January 6, 1975, however, locates within a few hundred meters of the 1966 hypocenter. While these results support the hypothesis of a "Parkfield asperity" controlling nucleation of Parkfield mainshocks, the close proximity of the January 1975 event to the 1966 main shock raises new questions about the conditions required to initiate a characteristic Parkfield earthquake.

4. We are involved in the development of a new rapid earthquake notification and response system to replace the current system which, among its limitations, relies on obsolete hardware. As a module for this new system, we have developed an algorithm (RTP) to pick P-arrivals in real time from local earthquake seismograms. Picks are associated and events are located by downstream modules.

The new RTP is designed to emulate existing RTP programs (Allen, 1978). Like Allen's RTP, our program makes picks based not on the raw seismic trace, but on changes in a "characteristic function" (CF) calculated from the trace. This function is a first approximation to the envelope function; it is always positive and is sensitive to changes in amplitude and frequency. Also like its parent, the new RTP operates on one sample at a time, saving only the previous sample for difference calculations. It works on multiplexed data channels, with no interaction between channels.

The picker scans each trace for seismic events, based on very-short-term/long-term amplitude ratios of the CF. It discriminates between earthquakes and noise events using information on the shape and duration of the signal. Noise events are not reported. For those picks the program interprets as earthquakes, it reports the following: pick time,
quality, polarity, station code, coda length, and other trace amplitude information. Filtering and triggering parameters used by the program can be fine-tuned to suit network signal characteristics to minimize picks from noise sources.

To aid in evaluating the performance of the picker, we have also developed a "test bed" package of functions written in S. Using these functions, one can plot seismic traces with the RTP picks overlain and then interactively make hand picks (figure 3). The picking algorithm can also be called as a function from within Splus, allowing the user to change filtering or triggering parameters and see the resulting picks. For 379 of the best quality picks (Q=0, quality assigned by RTP), the median time difference between hand- and RTP-picked arrivals was 0.01 sec, with the RTP pick one sample later than the hand pick. This one sample discrepancy is most likely due to the difference in picking styles between a human and a computer program. A human can look back at the record before the first break, the RTP cannot. For 33 quality=1 picks, the median time difference was 0.03 sec. The distribution is skewed toward late RTP picks due to emergent arrivals. The RTP reports polarities well (95% agreement).

We are currently running a test version of this RTP on a 50 MHz IBM 486 PC. With 256 channels at 100 samples per second, the program uses approximately 50% of the CPU to calculate the characteristic and associated functions for each sample. The remaining CPU is then available for the additional computations required in picking, evaluating and reporting. Some optimization in hardware and software may increase the efficiency by 20%.

Reports


Figure 1. Cumulative number of earthquakes in the Calaveras multiplet plotted by date of occurrence. Also shown are times of nearby M>6 events (Morgan Hill and Loma Prieta) and very close smaller earthquakes.
Figure 2. Cross section from NW to SE (A to A') along the San Andreas fault showing the JHD locations of the 1966 Parkfield mainshock and foreshock (stars) with respect to seismicity from 1975 to 1983 (left) and 1984 to April 1993 (right).
Figure 3. a) An 80 second long seismic trace with P-arrival times (short-dashed lines) and coda lengths (dot-dashed lines) determined by the RTF. Pick polarity and quality is shown above each pick. b-d) Two-second windows centered on each of the picks in a). e) Histogram of time difference between machine- and hand-picked arrivals of qualities 0-3 (as assigned by the RTP).
Investigations

1. **Travel-Time Tables.** Develop new standard global travel-time tables to locate earthquakes.

2. **Arrival-Time Data.** Coordinate planning for an International Seismological Observing Period (ISOP)—a time interval during which there would be enhanced reporting of arrival-time data.

3. **Earthquake Location in Island Arcs.** Develop practical methods to accurately locate earthquakes in island arcs.

4. **Subduction Zone Structure.** Develop techniques to invert seismic travel times simultaneously for earthquake locations and subduction zone structure.

Results

1. **Travel-Time Tables.** A major international effort within IASPEI over the last three years has led to the construction of two new global travel-time models for earthquake location and phase identification (iasp91, Kennett and Engdahl, 1991; and SP6, Morelli and Dziewonski, 1992). These radially stratified models have been constructed so that the travel times for the major seismic phases are consistent with the observations for events in the ISC Bulletin for 1964–1987. The baseline for the P-wave travel times in the iasp91 model has been adjusted to provide only a small bias in estimated origin time for independently constrained events at the main nuclear testing sites around the world. A set of algorithms has been developed (Buland and Chapman, 1983) that provides rapid calculations of the travel times of an arbitrary set of phases in these models for a specified source depth and epicentral distance.
Generally, differences in predicted travel times between the iasp91 and SP6 models are not significant—a few tenths of seconds. There are, however, certain classes of arrivals where the discrepancies are larger and the phase is important enough that the differences should be better understood. This presents a fundamental problem: exactly how lateral heterogeneity (and anisotropy) in the Earth's mantle and core contributes to the global variance in the teleseismic travel times of individual phases is not well understood. The differences between iasp91 and SP6 could therefore simply reflect the particular choices made in data selection and processing. It is quite possible that for many phases the global variance is large enough so that, for the current global data set, the two models are equally satisfactory.

To clarify these issues, a simple experiment is performed. First, a modified ISOP event-selection algorithm is applied to the ISC Catalog for 1964–1989. The selection algorithm has been designed so that selected earthquakes are not only rich in later phases, but also provide a relatively even global distribution of phase ray paths for the sampling of Earth structure. The selected events are then relocated in both models using P, pP and PKP arrivals to reduce errors in depth determination which are common for locations based solely on P-wave data. The relocation is performed for each model in an interactive manner and includes a re-identification of phases after each iteration. Since the upper and lower mantles in each model are virtually identical, the two models do not produce significantly different hypocentral parameters.

The emphasis in this work is to clarify the effects of lateral heterogeneity on the global travel times. Travel-time data for both P- and S-type phases are plotted globally over selected depth ranges to reveal effects produced by structure in different regions of the Earth. The plots clearly isolate systematics which are related to the lateral heterogeneity of the mantle. The data for direct P and S waves are surprisingly well correlated and illuminate features of the upper and lower mantle which are common to both data sets. Effects of lateral heterogeneity in the core are more problematic, as the travel times of core waves are seriously contaminated by lateral variations in the structure of the overlying mantle. Removal of these effects is a challenging problem that is now overcome only by using differential travel-time data for core phases.

2. **Arrival-Time Data.** The following is a short summary of recent ISOP activities:

In the summer and early fall of 1992, two major workshops were organized in Prague and Hong Kong. The 2-day Prague meeting in July 1992 focused on the effort to develop specialized software for ISOP-type analysis of seismograms. The Hong Kong meeting (AGU's Western Pacific Geophysics Meeting) in August provided an opportunity to run a full-day program to introduce Asian scientists to ISOP. Both workshops were well-attended and very successful. After the Hong Kong meeting E.A. Bergman traveled through southeast Asia, visiting seismo-
logical organizations in Malaysia, Indonesia, and the Philippines, encouraging these institutions to become involved in ISOP.

In September 1992, E.R. Engdahl gave a talk on ISOP at the Geoscope Symposium in Paris. In October, the IRIS DMS Standing Committee met in Golden and Boulder; a demonstration of the ISOP workstation software was made and discussions with the IRIS personnel regarding cooperation in ISOP held. In December, D. Doornbos (a “co-founder” of the ISOP project and member of the Steering Committee) visited Golden and assisted in planning the ISOP pilot project which was recently launched. Also in December E.A. Bergman attended the annual meeting of the FDSN and gave a short talk on the ISOP project, emphasizing the pilot project.

The Fall issue of the IRIS Newsletter carried an article on ISOP. An article in Tectonophysics in the fall of 1992: “ISOP in Africa” was also published. Reprints of this article were mailed to over a hundred ISOP correspondents in Africa and the Middle East.

In January, E.R. Engdahl and E.A. Bergman traveled to Albuquerque Seismological Laboratory, along with J. Johnson (co-developer of the PITSA-based ISOP software), for a day of demonstrations and talks on ISOP. Use of the GTSN system in ISOP was a major topic of discussion. ASL’s contacts with seismologists worldwide are an important opportunity for ISOP and many ASL personnel were still unfamiliar with the project.

F. Scherbaum attended an ISOP-oriented symposium at the European Union of Geosciences meeting in Strasbourg in April 1993, to represent the ISOP project. His talk focused on the use of small local networks in ISOP and attracted much interest. A member of the ISOP Steering Committee, N.V. Kondorskaya of Russia, was also in attendance and held discussions with many European seismologists. Also in April, E.R. Engdahl organized a special session on Regional Seismograph Networks and gave a talk on ISOP at the meeting of the Seismological Society of America, held in Mexico.

At the Spring 1993 AGU meeting, F. Scherbaum ran a very successful mini-course on “First Principals of Digital Signal Processing for Seismologists.” This course is being developed for use in ISOP training courses worldwide; in fact, we are planning to hold an expanded version in Brazil in August 1994.

The ISOP pilot project was launched on September 1, 1993. This involves about two dozen stations worldwide carrying out ISOP-type analysis on events designated at NEIS. This activity is intended to test many of the logistical arrangements for the full ISOP observing program, and stimulate needed improvements both at the stations and at NEIS. It is also an excellent opportunity to test the ISOP software.
A major effort over the last year has gone into the development of the ISOP software, partly under a contract between the USGS and F. Scherbaum, partly with support from IRIS, and partly with support from the U.S. Czech Science & Technology Agreement, under which E.A. Bergman is working with A. Plesinger. The software and related documentation are close to completion, at least to the extent needed for initial distribution, and we expect to introduce these products at the IASPEI Assembly in Wellington in January 1994. A great many people are awaiting the release of this software and we are very excited to finally put it in the hands of users.

In support of a grant under the U.S.-Czech S&T Agreement, E.A. Bergman spent a month in Prague recently, working on documentation for the software, and visiting several observatories which are participating in the ISOP pilot project. This provided a very useful perspective on how the ISOP observing program will look to the participants.

The ISOP Newsletter is continuing to be published several times a year. The most recent issue was published in March 1993. The ISOP Office continues to collect and distribute a number of publications and resources (e.g., software) for the benefit of the ISOP community. The ISOP Office has become a widely recognized source of information on a variety of topics of interest to the international seismological community, and a considerable effort must go into answering these requests.

3. Earthquake Location in Island Arcs. Seismicity occurring along the Aleutian arc between 1957 and 1991 is cataloged and relocated. Two great earthquakes ruptured the same 250 km-long portion of the central Aleutian arc: the 1957 Aleutian Islands earthquake and the 1986 Andreanof Islands earthquake. Earthquake relocations are based on P-wave arrival times published in the ISS, BCIS, and ISC bulletins and include corrections for the near-source velocity structure associated with the downgoing slab. Magnitude estimates are extracted from bulletins and prior to 1964 are estimated by us from microfilmed records. The catalog is complete above magnitude 5.5. Aftershocks associated with the 1957 and 1986 earthquakes are spatially anticorrelated. If the aftershock distributions are interpreted as rimming the distribution of seismic moment release associated with each event, this implies the moment distribution of the 1986 earthquake is anticorrelated with that of the 1957 earthquake. This observation suggests that caution should be used in identifying mechanically strong portions of a fault, asperities, by simply mapping the moment distribution of a single great earthquake. A fundamental tenet of the asperity model, that rupture always occurs on the strongest portion of the fault with weaker portions rupturing either aseismically or dynamically as a result of rupture on a strong fault patch, may in the case of the central Aleutian arc not be correct. Thus, observing the moment distribution from a single great earthquake may tell little about what the distribution of moment release will look like during the next earthquake.
4. **Subduction Zone Structure.** Compressional body waves from earthquakes in the central part of the Tonga-Kermadec subduction zone arrive very early in New Zealand stations (Ansell and Gubbins, 1986), and the waveforms of these phases are often characterized by an emergent high-frequency precursor. Examples of these slab phases have been collected from short-period seismograms of SRO station SNZO in Wellington, and from Leeds' POMS array of nine 3-component broad-band seismometers in the Tararua Mountains, New Zealand.

Gubbins and Snieder (1991) explained both the early arrivals and the body-wave dispersion by P-wave propagation through a high-velocity layer in the Tonga-Kermadec subduction zone. The absence, however, of detailed information about the morphology of the Tonga-Kermadec subduction zone prohibited the establishment of the relation between slab structure and observed waveforms.

With the objective to further investigate the relation between the frequency characteristics of the digital seismograms and propagation through subducted slab, a tomographic study is performed to determine the morphology of the Tonga-Kermadec subduction zone. For the tomographic study, an approach similar to that described by Van der Hilst et al. (1991) is followed. The earthquakes are relocated in the iasp91 model for P- and S-wave velocities (Kennett and Engdahl, 1991) and computed travel-time residuals for P and pP phases relative to the iasp91 travel-time tables computed. In the linear inversion for aspherical Earth's structure, about 1,100,000 P and 35,000 pP data were used. By incorporating data of the pP phase, the sampling of shallow slab structure is improved, in particular below regions where only few seismological stations are located. New tomographic images depicting aspherical variations in P-wave velocity associated with the Tonga-Kermadec subduction zone are constructed.

**Reports**


Three-Dimensional Plate Boundary Structure in the San Francisco Bay Region: Implications for the Earthquake Cycle

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Scope of Project

The 3-D plate boundary structure in the San Francisco Bay region is complicated by offset between the surface trace of the San Andreas fault and the locus of strain accumulation beneath the seismogenic crust. Several approaches are being used to both define this complex plate boundary structure and better constrain the consequences of such a boundary for the earthquake cycle in the region. Three sub-projects are being undertaken in this regard: (1) Crustal seismic tomography of the San Francisco Bay region; (2) 3-D finite element modeling of intra-seismic strain patterns in the region; and (3) Modeling of stress response to simulated seismic events along segments of the San Andreas and East Bay faults.

Crustal Seismic Tomography

In conjunction with the Bay Area Seismic Imaging eXperiment (BASIX), which has a goal of delineating crustal structure and fault/shear zone geometries, we have undertaken a 3-D tomographic study of crustal structure in the S.F. Bay region. This study utilizes natural earthquake sources recorded at the Northern California Seismic Network in combination with artificial sources (both explosions and BASIX airgun) recorded by CalNet and temporarily deployed seismographs. We have been able to determine a well constrained 3-D velocity structure for the region for the upper and middle crust (depth < 20 km). This velocity model is now being refined and applied to studies of relationships among seismic velocity, thermal structure and depth extent of earthquakes; with an emphasis on these processes along the San Francisco Peninsula.

3-D Finite Element Strain Modeling

The utilization of finite element modeling is allowing us to place better constraints on the allowable plate boundary geometry in the S.F. Bay region. We are using the code TECTON and use a fully temperature dependent visco-elastic rheology to simulate crustal and upper mantle conditions. This aspect of the project is also linked to the BASIX as we are incorporating structural information determined from BASIX in our models to test the effects of such features on the deformation pattern in the region. With this modeling we can confidently conclude that strain in
the lithospheric mantle of the San Francisco Bay region is concentrated in the vicinity of the East Bay faults (Hayward, Calaveras, Rodgers Creek, etc.). Additionally, via this modeling, we are investigating the nature of the crustal terrane cored by the Salinian block along the west side of the San Andreas through the Santa Cruz Mountains and the S.F. Peninsula. Our modeling indicates that it is partly decoupled from its underlying Pacific plate, and has moved somewhat independently of the Pacific plate. This terrane also serves as a load depressing the lithosphere beneath the San Francisco Bay and our modeling indicates that the emplacement of the Salinian/Santa Cruz terrane over the Pacific Plate may serve as the driving force for S.F. Bay subsidence.

**Stress Response and the Earthquake Cycle**

The possibility that events on one fault strand may enhance the seismic potential of other linked faults in the San Andreas system is being evaluated in this aspect of our project. Again we are using 3-D finite element modeling (with visco-elastic rheologies) to simulate the effect of stress buildup, relief and redistribution during the earthquake cycle. In this modeling we can evaluate not only the static stress change (primarily the elastic response) but also the pattern of stress response throughout the earthquake cycle. At this stage, this modeling indicates that patterns of stress response when full 3-D viscous effects are incorporated are significantly different from the response of elastic (and quasi-viscous) models. of particular interest in this project is the large spatial variation in stress recovery rates along different segments of the faults.

**Publications Related to Project**

Papers:


Furlong, K.P., and D. Verdonck, 1994, Three-dimensional lithospheric kinematics in the Loma Prieta region: Implications for the earthquake cycle (Chapter), USGS Professional Paper on the Loma Prieta Earthquake (in press)
Abstracts:


Furlong, K.P., and D. Verdonck, 1993, Stress history of faults in the San Francisco Bay region during simulated Earthquake cycles, EOS trans. AGU (Abstract supplement)
THEODOLITE MEASUREMENTS OF CREEP RATES ON SAN FRANCISCO BAY REGION FAULTS

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Grant Number 14-08-0001-G1992
Program Element II.2

We began to measure creep (aseismic slip) rates on San Francisco Bay region active faults in September 1979. Over the past 14.2 years, we have made over 1400 creep measurements, with over 550 of these occurring in the four years following the Loma Prieta earthquake (LPEQ). Amount of slip is determined by noting changes in angles between sets of measurements taken across a fault at different times. This triangulation method uses a theodolite to measure the angle formed by three fixed points to the nearest tenth of a second of arc. Each day that a measurement set is done, the angle is measured 16 times and the average determined. The amount of slip between measurements can be calculated trigonometrically using the change in average angle. The precision of our measurement method is such that we can detect with confidence any movement more than 1-2 mm between successive measurement days.

We presently have regular measurement sites at 29 localities on active faults, including 26 in the San Francisco Bay region (see Figure 1). We also have one measurement site on the San Andreas fault in the Point Arena area and two on the Maacama fault in Willits and Ukiah that do not appear on Figure 1. During 1993 we remeasured most sites with a history of creep about once every two to three months and most sites without any creep history about every four to six months. Most sites span a fault width of about 50-225 m, but a few must span a greater width because of site considerations. The fault width spanned (W) is noted on Figures 2 through 5 and represents the distance from the theodolite on one side of a fault to a target on the other side of the fault. The figures also show the average rate of movement at each site as determined by the slope of the least-squares line which also appears on each of the graphs. The graphs also show the time of the 17 October 1989 LPEQ as a vertical line. The following is a brief fault-by-fault summary of our results through 30 November 1993.

SAN ANDREAS FAULT (see Figure 2) - We have been measuring horizontal slip on the San Andreas fault at Site 14 at the Point Reyes National Seashore Headquarters for 8.6 years and at Site 10 in South San Francisco for 13.5 years. Both sites have shown virtually no net slip and neither was affected by the LPEQ thus far.

In November 1989, we began measuring a USGS site (our Site 22) in Woodside that had not been remeasured for many years. Our results compared to unpublished USGS measurements in 1977 show that virtually no surface slip occurred between 16 February 1977 and 4 November 1989 and very little has occurred since.
We also established in November 1989 Site 23 on the San Andreas fault near the southeastern end of the LPEQ aftershock zone and northwest of San Juan Bautista. Very little net slip has occurred at this site in the past four years.

In July 1990, we established Site 25 on the San Andreas fault just southeast of San Juan Bautista and the aftershock zone. This site is on the central creeping portion of the fault and has been moving at a rate of 14.6 mm/yr for the past 3.3 years. This is considerably faster than the longer-term pre-LPEQ rate of about 7-8 mm/yr as determined by a USGS creepmeter at this site (Schulz, 1989; Gladwin and others, 1991).

Site 18 in the Point Arena area has averaged 1 mm/yr of right slip in the 12 years between 9 January 1981 and 11 January 1993.

In summary, the San Andreas fault at five measurement sites (18, 14, 10, 22, 23) along the previously locked portion of the fault both northwest and southeast of the LPEQ aftershock zone does not appear to have been affected by the LPEQ in the four years since October 1989. This portion of the San Andreas fault has remained virtually locked, with 1 mm/yr or less of creep occurring along it. In contrast, the post-LPEQ creep rate on the northwestern portion of the central creeping segment of the fault at Site 25 near San Juan Bautista is about twice the longer-term, pre-LPEQ creepmeter average.

**HAYWARD FAULT** (see Figure 3) - We have been measuring horizontal slip at five sites along the Hayward fault for 13.2 to 14.0 years and have determined that the overall right-lateral creep rate is about 4.2 to 4.9 mm/yr. Although the creep characteristics (steady or episodic) differ from site to site, the overall rates are quite similar. A detailed analysis of our results indicates that the LPEQ caused an overall slowdown in the rate of right-lateral creep along the Hayward fault, particularly near the southeastern end of the fault in Fremont. A detailed discussion of the pre-LPEQ and post-LPEQ creep rates on the Hayward fault is beyond the scope of this summary but can be found in Galehouse (1994).

In the 13.2 years since we began measurements in August 1980 in San Pablo (Site 17) near the northwesterly end of the Hayward fault, the overall average rate of right slip (about 4.2 mm/yr) has been slightly slower, but similar to the overall rates at the other Hayward fault sites. However, superposed on the overall slip rate in San Pablo are changes between some measurement days of up to nearly a cm in either a right-lateral (more common) or left-lateral (less common) sense. This pattern was more pronounced between mid-1980 to mid-1986 and has been somewhat less pronounced since. It is probable that the results at this site are influenced by the seasonal distribution of rainfall (Lienkaemper and others, 1993).

The Hayward fault at Site 13 on Rose Street in Hayward also moves somewhat episodically, but not as pronounced as in San Pablo. With J. Lienkaemper of the USGS, we remeasured curb offsets and old City of Hayward arrays at Rose Street in late 1992 and determined that the overall creep rate there since 1930 is 5 mm/yr. This is virtually the same rate (4.9 mm/yr) that we have measured for the past 13.2 years (see Figure 3).

Extremely uniform movement characterizes Site 12 on D Street in Hayward. Two active traces of the Hayward fault occur here and their combined movement rate has been about 4.5 mm/yr for the 13.4 years since we began measurements in June 1980.
Movement along the Hayward fault at Site 2 in Union City has also been fairly uniform but somewhat more episodic than movement at Site 12. Site 2 has been moving at a rate of about 4.7 mm/yr for the 14.0 years since we began measurements in September 1979.

Since we began measuring Site 1 in Fremont in September 1979, the fault has moved rather episodically. Typical surface movement characteristics are relatively rapid right slip of about a cm over a few months time alternating with relatively slower slip over a period of two or more years. The fault at Site 1 was in one of the relatively slower phases of movement prior to the LPEQ and the slower phase persisted for a total of about five years, including about three and one-half years following the LPEQ. The average rate of right-lateral creep during this slow period was less than 1 mm/yr. The creep rate before the LPEQ was 5.4 mm/yr but the extended slow phase has brought the overall average down to 4.6 mm/yr for the past 14.0 years. The slow phase ended here between March and May of 1993 when more than a cm of right slip occurred.

In February 1990 we established Site 24 on the Hayward fault on Camellia Drive in Fremont, about four km southeast of Site 1 (see Figure 1). Although relatively rapid right-lateral creep had been reported for this site in recent years, we have measured very little net slip. In fact, our results indicate a slight amount of left-lateral creep since the LPEQ. Measurements since April 1992 at Parkmeadow Drive in Fremont (Site 27) only 0.4 km southeast of Site 24 also indicate a small amount of left-lateral creep (not shown on Figure 3).

In summary, the right-lateral creep rates on the Hayward fault from Site 17 in San Pablo to Site 1 in Fremont are now about the same as they were before the LPEQ. However, the southeasternmost portion of the fault in Fremont at Site 24 and Site 27 still shows a slight amount of post-LPEQ left-lateral slip. All these changes are consistent with Reasenberg and Simpson's (1992) calculations of static stress changes due to the LPEQ (also see Gatehouse, 1994).

In order to fill in the large data gap between Site 17 in San Pablo and Site 13 in Hayward, we began measuring three new sites on the Hayward fault in early 1993. Site 28 is on Encina Way and Site 29 on La Salle Avenue, both in Oakland. Site 30 is on Florida Avenue in Berkeley (see Figure 1). Very preliminary results suggest a somewhat faster than average Hayward fault creep rate at Site 28 and slower than average rates at Site 29 and Site 30.

**CALAVERAS FAULT** (see Figure 4) - We have been measuring horizontal slip at two sites on the Calaveras fault in the Hollister area for 14 years. Slip at both sites has been episodic with intervals of relatively rapid right slip typically lasting a couple months or less alternating with longer periods of time when little net slip occurs. The LPEQ occurred during an interval of slower movement that had persisted for about a year at Site 4. The earthquake apparently triggered up to 14 mm of right slip at Seventh Street (see Figure 4). Overall the rate of right slip is about 7.1 mm/yr for the past 14.1 years.

Slip at Site 6 along Wright Road just 2.3 km northwest of Site 4 is also episodic. The LPEQ occurred during an interval of slower movement that had persisted for about a year at Wright Road (similar to the situation at Seventh Street). The earthquake apparently triggered up to 12 mm of right slip. The overall rate of slip at Wright Road is 10.1 mm/yr. This rate is about 3 mm/yr faster than the rate at nearby Seventh Street. Either the creep rate decreases significantly from Wright Road southeast to Seventh
Street or undetected surface movement is occurring outside our 89.7 m-long survey line at Seventh Street.

After the rapid slip triggered by the LPEQ, both sites in the Hollister area returned to a slower mode of movement which has now persisted for four years at Site 6. The slowdown was not as pronounced at Site 4 and the pre- and post-LPEQ rates are now about the same. At Site 6, however, the slip rate decreased from a pre-LPEQ rate of about 12.2 mm/yr to a post-LPEQ rate of less than 2 mm/yr. This has brought the overall average down to 10.1 mm/yr which has resulted in what appears to be a "slip deficit" of about 2 cm at Site 6 at the present time (see Figure 4). A more detailed discussion of the effect of the Loma Prieta earthquake on the Calaveras fault in the Hollister area is in Galehouse (1990). This paper also discusses the effect of the Morgan Hill earthquake in 1984. No immediate surface displacement had occurred at either of the Hollister area sites when they were measured the day after the Morgan Hill earthquake. However, within the following 2.5 months, both sites showed over a cm of right slip which was followed by a relatively long interval of slower slip (see Figure 4). A more detailed discussion of the longer-term effect of the LPEQ on the Calaveras fault is in Galehouse (1994).

In contrast to the sites in the Hollister area, Site 19 in San Ramon near the northwesterly terminus of the Calaveras fault was not affected by the LPEQ. It has remained virtually locked throughout our 12.8 years of measurements.

CONCORD - GREEN VALLEY FAULT (see Figure 5) - We began our measurements at Site 3 and Site 5 on the Concord fault in the City of Concord in September 1979. It appears that typical movement characteristics at both sites are intervals of relatively rapid right slip of about 7-10 mm over a period of a few months alternating with intervals of relatively slower right slip of about 1-2 mm/yr over a period of several years. For the past 14 years, the overall average creep rate along the Concord fault in the City of Concord is about 3 mm/yr (3.4 at Site 3 and 2.7 at Site 5).

It appears that the LPEQ had little or no effect on the Concord fault at the measurement sites in the City of Concord. As shown in Figure 5, the latest phase of relatively rapid right slip occurred at both sites on the Concord fault in late 1992 - early 1993. It does not appear to be related to any seismic event(s).

We began measuring Site 20 on the Green Valley fault near Cordelia in June 1984. Large variations tend to occur at this site between measurement days, possibly because of the seasonal effects of rainfall and because logistical considerations resulted in our survey line being particularly long (335.8 m). However, our results suggest that the Green Valley fault behaves similarly to the Concord fault i.e., relatively rapid right slip in a short period of time (months) alternating with relatively slower slip over a longer period of time (years). The Green Valley fault was in a period of relatively slower movement for the first 20 months of our measurements, averaging a few mm/yr of right slip. In early 1986, however, the fault slipped right-laterally more than a cm. This was followed by about three years in which the net slip was less than 1 mm/yr. Sometime after 6 August 1989, the Green Valley fault entered into another phase of relatively rapid right slip that had totaled about 2 cm by late 1990. Since then, however, the overall net slip has been left-lateral which has brought the overall average down to 4.7 mm/yr for the past 9.3 years and has resulted in a "slip deficit" of about 2 cm.

Regarding the relationship between the Green Valley and Concord faults, the episodes of relatively rapid slip and relatively slower slip do occur at different times.
and the rate of slip is higher on the Green Valley fault. The episodic nature of the slip and the duration of the faster and slower intervals, however, are similar. Based on these similarities and the small step between their respective trends, we consider the Concord and Green Valley faults to be different names for the southeastern and northwestern segments of the same fault system.

RODGERS CREEK FAULT - We measured a site (16) on the Rodgers Creek fault in Santa Rosa from August 1980 until we had to abandon it for logistical reasons in January 1986. During these 5.4 years of measurements, no significant surface slip occurred and we concluded that the Rodgers Creek fault was not creeping at this site. In September 1986, we established Site 21 on the Rodgers Creek fault near Penngrove (see Figure 1). The average at Site 21 was about 1-2 mm/yr for the next six years. However, in mid-1993, we discovered that one of our triangulation points had become unstable and the site will have to be reconfigured or relocated. At present, it is difficult to know whether or not the Rodgers Creek fault is really creeping slowly or whether the low rate is due to the "noise" level at this particular measurement site. The LPEQ does not appear to have had any effect on the Rodgers Creek fault at Site 21.

WEST NAPA FAULT - We began measurements at Site 15 in the City of Napa in July 1980. Similarly to the situation at Site 21 on the Rodgers Creek fault, there tends to be a lot of surface "noise" at this measurement site. However, the average rate of right slip on the West Napa fault over the past 13 years is less than 1 mm/yr. In other words, the West Napa fault is virtually locked at the surface with no creep occurring. The LPEQ does not appear to have had any effect on our results for the West Napa fault.

SEAL COVE-SAN GREGORIO FAULT - We began measurements at Site 7 on the Seal Cove fault segment in Princeton in November 1979. The least-squares average indicates that virtually no creep has occurred at this site over the past 13.8 years. We began measuring Site 8 on the San Gregorio fault segment in May 1982. This site shows very large variations from one measurement day to another, probably due in part to the particularly large fault width (452 m) measured. The least-squares average shows virtually no creep for the past 11.3 years. Therefore, the Seal Cove-San Gregorio fault is not presently creeping and the LPEQ does not appear to have had any noticeable effect on the rate of movement at either of the sites on this fault system.

ANTIOCH FAULT - We began measurements at Site 11 in the City of Antioch in May 1980. The average rate of movement has been virtually zero for the past 13.3 years. Site 9 just south of town showed 1.7 mm/yr of right slip for the 7.6 years from 21 November 1982 to 1 July 1990. New construction then destroyed our measurement array at this site. We have noted that much subsidence and mass movement creep occur both inside and outside the Antioch fault zone in the area of our two measurement sites and it is probable that these nontectonic movements are influencing our measurement results. If any tectonic creep is occurring along the Antioch fault, it is probably at a very low rate. The LPEQ does not appear to have had any noticeable effect at either of the sites on the Antioch fault.
MAACAMA FAULT - The Maacama fault extends from northern Sonoma County to north of Laytonville in Mendocino County and is the northwesterly continuation of the Hayward-Rodgers Creek fault trend. We began measurements at Site 26 in Willits in November 1991. Preliminary results over the past two years indicate that the Maacama fault is creeping right-laterally at about 4-5 mm/yr which is similar to the creep rate on the Hayward fault. We established a second site (31) on the Maacama fault just east of Ukiah in May 1993. It has shown a small amount of right slip thus far.

REFERENCES CITED


PUBLICATIONS


Figure 1. Numbered dots are San Francisco State University theodolite measurement sites. Epicenters and magnitudes are indicated for the 24 April 1984 Morgan Hill earthquake (MHEQ) and the 17 October 1989 Loma Prieta earthquake (LPEQ).
SAN ANDREAS FAULT

Figure 2. San Andreas Fault Displacement (1980 - 1994)
Figure 3. Hayward Fault Displacement (1979 - 1994)
CALAVERAS FAULT

SF-19 SAN RAMON (Corey Place)
0.2 ± 0.1 mm/yr for 12.8 yrs
W = 111.1 meters

SF-06 HOLLISTER (Wright Road)
10.1 ± 0.3 mm/yr for 14.0 yrs
W = 51.7 meters

SF-04 HOLLISTER (Seventh Street)
7.0 ± 0.1 mm/yr for 14.1 yrs
W = 89.7 meters

MHEQ = Morgan Hill Earthquake of 24 Apr 84
LPEQ = Loma Prieta Earthquake of 17 Oct 89

Figure 4. Calaveras Fault Displacement (1979 - 1994)
CONCORD - GREEN VALLEY FAULT

SF-20 GREEN VALLEY FAULT (near Cordelia)
4.7 ± 0.3 mm/yr for 9.3 yrs
W = 335.8 meters

SF-05 CONCORD (Salvio Street)
2.7 ± 0.1 mm/yr for 14.0 yrs
W = 57.1 meters

SF-03 CONCORD (Ashbury Drive)
3.4 ± 0.1 mm/yr for 14.0 yrs
W = 130.0 meters

LPEQ = Loma Prieta Earthquake of 17 Oct 89

Figure 5. Concord - Green Valley Fault Displacement (1979 - 1994)
Holocene Interseismic Deformation and Stratigraphic Modeling of the Earthquake Cycle, Kodiak Islands, Alaska
Award No. 1434-93-G-2316

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Investigations Undertaken

I. 1993 Progress

In the last year we have spent over 120 man-field-days completing the following tasks: (1) field surveys of 13 tidal benchmarks previously occupied in 1964-65 after the 1964 Great Alaskan Earthquake as well as 7 tidal benchmarks dating back as far as 1908 (Figure 1), but which were not reoccupied after the 1964 event; (2) Tidal elevation data on intertidal marsh geomorphology and vertical vegetation zonation in association with benchmark surveys; (3) Shoreline mapping in areas of the Kodiak Islands where tidal benchmarks were visited; (4) Reoccupation of marsh sample sites visited in 1991-1992 field seasons; (5) sample data reduction, micro-paleontology analysis of selected peat samples, and 14-C dating of "event" horizons in selected locations.

II. Paleoseismic Investigation

The growing body of interseismic deformation data from the Kodiak Islands has given new incite into the marsh stratigraphy and the record of paleoseismicity. The rapid rebound of the land level after the 1964 earthquake explains the occurrence of peat couplets, which are alternating salt water and fresh water affinity peat layers. Some of these layers are separated by a fine to coarse sand and fine gravel layer that we interpret as a tsunami deposit.
Several of these couplets have recently been subject to a micro-paleontologic analysis. Eileen Hemphill-Haley (USGS, Pacific Marine Branch) has identified diatoms from three of our field identified couplets. These stratigraphic "events" are characterized by an abrupt change from Triglochin maritima peat to a Triglochin-free peat and we believe are indicative of approximately 1 m of vertical elevation change. At one site on Sitkalidak Island (Figure 1) which is located trenchward of the zero isobase of 1964 coseismic deformation and emerged between 0.5 (0.16m) and 2.2 ft (0.72m) (Plafker, 1969), the association of peats and diatoms indicates an abrupt uplift where the fresh water affinity diatoms in the Triglochin-free peat are overlying a triglochin-rich horizon with brackish to marine affinity diatoms. This event has a calibrated calendar age of 673-526 years BP (All sample ages are calibrated calendar ages from Stuiver and Reimer, 1993, with a 2x lab error and a 2 sigma counting error.)

Another site, on Shuyak Island, shows an abrupt submergence "event" in the stratigraphy, dated by $^{14}$C at approximately 1300 years BP, is indicated by the peat and diatom sequence. This site submerged approximately 3.2 ft (1.05m) as a result of
the 1964 earthquake. This site has two dated events as shown on Figure 2. The upper event dated at 532-459 yr BP may be the same event as identified at Sitkalidak Island. Although the diatom analysis indicates a change between the two peats in this younger couplet, more work is necessary to identify the details of this change. The older "event" dated at approximately 1300 yrs BP shows an abrupt change between the two peats in the couplet and indicates submergence. This "event" may correlate with a paleoseismic event identified at Middleton Island and Copper River Delta at the eastern end of the 1964 earthquake rupture zone (Plafker and Rubin, 1967; Plafker and Lajoie, 1992).

Additional marsh section samples are at the Quaternary Isotope Lab (University of Washington) for 14C dating and diatom analyses are in preparation.

III. Earthquake Cycle Model

To better understand the stratigraphy in the Kodiak Island marshes we have attempted to model the earthquake cycle on the Kodiak Islands. To constrain the parameters of the earthquake cycle model we have used our field stratigraphic logs and, as a trial, tide gauge data presented by Savage and Plafker (1991). We will refine this with the tidal data collected from a large area of the islands this last field season (See section below; Figure 1). For a first approximation we assumed that the 1964 earthquake is a characteristic event. To generate the saw-tooth curve on Figure 2 we need to constrain the following parameters: coseismic uplift, interseismic uplift and the earthquake recurrence interval. In order for the conditions to be favorable for marsh sedimentation the saw-tooth curve must roughly parallel the Holocene sea level curve.

The available tide gauge data includes a 39 year window about the 1964 earthquake. As determined from the Kodiak permanent tide gauge (Savage and Plafker, 1991) the interseismic uplift rate for the 14 year period immediately preceding the 1964 earthquake is 4.8 mm/yr. We assume that the distribution and magnitude of coseismic deformation as mapped by Plafker (1969) is repeated in each paleo-event and is followed by an exponentially decaying uplift rate curve determined by the initial post-1964 rate of 20mm/yr in the 10 years following the earthquake to an average of 17 mm/yr in the subsequent 10-25 year period. Our model stratigraphic sample section shown in Figure 2 from Shuyak Island is located in an area that experienced approximately 1 meter of subsidence in the 1964 event (Plafker, 1969). An average recurrence of 750 years is assumed from the Copper River Delta record (Plafker and Lajoie, 1992).

We are unable to explain the occurrence of the marsh stratigraphy on any of the islands using these parameters. The given parameters demand a long term uplift rate of 8 to 8.5 mm/yr. Our model for Shuyak Island is shown on Figure 2, and requires either a lower interseismic rate, a greater coseismic uplift (-) or shorter recurrence interval, otherwise there would be no marsh sediment accumulation. Figure 2 shows a saw-tooth curve that can accommodate the marsh stratigraphy observed, however a very steep post-seismic rebound is necessary and the 4.8 mm/yr preseismic uplift is not accommodated. The dashed line on one of postseismic curves shows an alternative uplift curve that would accommodate the 4.8 mm/yr preseismic uplift.
Cumulative Uplift
Earthquake Cycle Deformation
(t* = 100; R1 = 750 yr; C.S. = 1 m)

Numbers correspond to horizons shown on section below.

BIG BAY A-4
SHUYAK ISLAND

Elevation in meters with respect to mean high water; for HHW subtract 1.5 meters.

IDEALIZED STRATIGRAPHIC MODEL
SHUYAK ISLAND
KODIAK ISLANDS, ALASKA
FIGURE 2
IV. Postseismic Movements

An alternative explanation for the observed marsh stratigraphic sequence may be revealed by the tidal benchmark data we collected during the 1993 field season. Twenty tidal benchmarks were reoccupied (13 last occupied in 1964-65; 7 dating back to 1908) for a minimum of four tidal minimum or maximum. Wind velocities, wave amplitudes and local air pressure changes were recorded at the time of the benchmark surveys. When possible, more tidal cycles were measured at the individual benchmarks. Favorable weather conditions with minimal fluctuations in air pressure or wind direction and velocity for much of July and August enabled us to reduce the errors normally associated with these variables.

The raw tidal benchmark readings vary between 0.8 and 2.43 feet of uplift since the last occupation (1964-1965). These readings show a local maximum in the area of Women's Bay, Kodiak Island, the location of the permanent tide gauge station, and the approximate hingeline of coseismic deformation. The post-seismic uplift drops dramatically to the NE and SW of this hingeline. In addition, two benchmarks occupied in 1968 and 1981 will provide intermediate points on the curve defining the post-1964 land level rebound. We are awaiting the initial survey data from NOAA that established these tidal benchmarks.

These land level changes measured by reoccupation of the tidal benchmarks represent a recovery of 30 to 200% of the coseismic subsidence. This recovery averaged 62% for all of the benchmark locations. Error analysis of this data is not complete, however individual readings will be corrected with the aid of a local weather service hourly recorded barograph, and the permanent tide gage record from Women's Bay. These should show any abnormal fluctuations in air pressure or sea surface level that were not recognized at the time of the benchmark survey.

Program Elements

This project addresses four of the 1993 program elements set forth in the Request for Proposals: (1) determine the geological and geophysical setting and characteristics of seismically active regions (Element II.1); (2) provide improved models of the tectonic setting of the forearc region (Element II.4); (3) conduct field investigation for evidence of late Holocene groundshaking associated with past subduction zone events (Element II.5); and (4) develop quantitative models of the complete earthquake cycle and test against relevant observations (Element 1.2).

Reports Published

The results of this award and a previous USGS NEHRP Award No. 14-08-0001-G2121 are part of a Ph. D. dissertation by the PI Gilpin at the University of California. Abstracts have been published at several meetings including American Geophysical Union 1991 (Gilpin et al., 1991) and 1993 (Gilpin and Carver, 1993) Fall meetings and for the 1992 Wadati Conference on Great Subduction Zone Earthquakes in Fairbanks, Alaska (Gilpin and Carver, 1992; Carver and Gilpin, 1992). The Ph.D. dissertation will be composed of three publishable articles that will represent the bulk of the data.
collected during the course of these two awards.

References


DEEP BOREHOLE PLANE STRAIN MONITORING
14-08-0001-G1812

Program Element II.7

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ACTIVITIES

Initial data from two tensor strain instruments installed in November 1991 along the southern Hayward fault at Anthony Chabot Park (CHT) and Garin State Park (GAT) were analysed and very preliminary calibrations developed. CHT was deployed at 127 m, and GAT at 154 m, at depths determined from core samples. The sites were intended to have co-located dilatometers from DTM, Carnegie Institution of Washington, but only at the Garin site is the dilatometer fully operational, so that the planned redundancy has not been achieved at the Chabot site. The up hole electronics are installed in underground vaults, which also house seismometers and recording instruments. The tensor instruments also include prototype pendulum dual axis tiltmeters. The electronics used is compatible with other tensor sites in California, and provides 30 minute samples only.

In general, all electronics in the BTSM sites are designed to be fully solar powered, ensuring isolation from the mains power grid. To accommodate State authority requirements that solar power not be used at these sites, uphole electronics at these two sites were modified to run from mains power. This power was not actually installed at the sites until April, 1993, so there was a considerable loss of initial data collection. The instruments were connected to mains power in June, and since then there have been several instrument shutdowns caused by large voltage transients on the supply. Work is continuing to eliminate these problems with the power source. To reach the performance standards of previous installations, it may yet be necessary to negotiate for solar powering of these sites as the only reasonable option for the isolation necessary for the remote capacitance measurement. As of December, 1993, both sites are operating to specification.

Routine data processing was carried out to provide an uninterrupted, interpreted data stream for the Parkfield experiment. Processing and interpretation was provided for several declared alerts, though no strain anomalies of significance occurred. Monitoring to ensure integrity of data sets from the seven U.S. instruments continued. A tensor strain data archive is provided in the Menlo Park data bases, and automatic processing of incoming signals provides real time access for Survey staff during alerts. In addition, regular analysis of the Parkfield data was reported to the now quarterly Parkfield experiment meetings.

Tidal calibration procedures were further refined, in collaboration with D. Agnew and F. Wyatt from U.C.S.D. The importance of site topography and geology at several of the Californian sites has been demonstrated, and procedures based on finite element
methods for correction of the calibration procedure have been investigated.

BCSM strain data from the Landers earthquake ($M_L 7.4$ on June 28, 1992) near Pinon Flat were analysed and compared with laser strain data and GPS data in collaboration with D. Agnew and F. Wyatt from U.C.S.D.

A sequence of small earthquakes ($M_L 3.2 - 3.7$) occurred near San Juan Bautista in December 1992. Large coseismic offsets were triggered by these events and significant postseismic strains were observed at the SJT instrument, as well as on dilatometers nearby at SRL and EVS. A characteristic strain/creep event, the nineteenth recorded to date, was recorded on the XSJ2 creepmeter following the sequence. This sequence is unique in the program demonstrating a large amplitude (more than a microstrain in fault parallel shear) subseismic event (a slow earthquake) occurring over several days duration at sites separated by many kilometers. The event remained below the limit of observation by geodetic measurements in place in the area. These data were investigated in detail, in collaboration with A. Linde of D.T.M., Carnegie Inst. of Washington, and with M. Johnston and K. Breckenridge of U.S.G.S., Menlo Park.

Three papers, detailing results of investigations of both pre- and post Loma Prieta strain data and tidal amplitudes were published in U.S.G.S. Professional Paper volumes concentrating on the Loma Prieta earthquake. A paper reporting a continuing series of strain events associated with episodic creep events at San Juan Bautista is in press. Data were provided for collaborative work on conference papers on the strain instrumentation installed along the Hayward fault, and on relating seismicity, creep and strain in the Parkfield region. The project staff were involved in three papers in the Fall AGU meeting in 1993.

RESULTS

BCSM strain data associated with the Landers earthquake in June, 1992 is illustrated in Figure 1. This data conflicts with laser strain data which had a 10 day exponential post-seismic decay on all three components. Whilst an explanation for this conflict is yet to be developed, comparison of data with tilt records suggests that observed ground water changes were not the source of the strain postseismic data. A reasonable explanation is that creep of near surface rocks following the large stress changes caused by the earthquake was the principle mechanism leading to regional postseismic strain of approximately 7% of coseismic strain.

Unexpectedly large strain offsets were observed coseismically with three earthquakes over the 11-12 December, 1992. Data illustrating these offsets is shown in Figure 2. The expected strain offsets determined from standard dislocation theory were an order of magnitude less than the offsets observed between two reading intervals (18 minutes apart) in each case. Furthermore extrapolation backwards to the exact earthquake time, using curves fitted to the large postseismic decays observed, indicated that a rapid postseismic decay process was present (with time scale of some minutes) as well as the decay with characteristic time of 1-5 days, evident in Figure 2. Analysis of the strain data signals in conjunction with routines modelling exponential growth on dislocation surfaces (developed by A. Linde) indicates a source region of the fault, with propagation of rupture or creep downwards from the surface following the initiating earthquakes which occurred at 5 km depth. A strain event occurred on 14 December coincident with a creep change recorded at XSJ2 (see Figure 3), and these data were typical of the characteristic creep/strain events previously reported for this location.

Investigation of the longer term strain data from this site shows a 100 - 200 day behaviour following these December events which is remarkably similar to that
observed following the Loma Prieta earthquake in October 1989 (see Figure 4). This correspondence is suggestive of a local readjustment of strain, and indicates the need for caution in the interpretation of any regional strain developments.

**RELEVANT PUBLICATIONS**


Gwyther, R. L., Gladwin, M.T. and Hart, R., A Shear Strain Anomaly Following the Loma Prieta Earthquake. *Nature* 356, 142-144, 1992


Figure 1. Individual gauge data from two components of the BCSM instrument at Pinon Flat during the Landers earthquake, June 28, 1992.

Figure 2. Areal strain ($\varepsilon_a$) and shear strains $\gamma_1$ and $\gamma_2$ observed at XSJ during the sequence of small earthquakes ($M_L$ 3.2 at 07:29 UT and $M_L$ 3.2 at 08:04 UT on Dec 11, and $M_L$ 3.7 at 15:53 and 15:58 UT on Dec 12, 1992) near San Juan Bautista. Note also the strain step on 14 December, a typical creep/strain event for this site.
Figure 3. SJT shear strains $\gamma_1$ and $\gamma_2$ shown over a period of hours, and corresponding creep data from XSJ2 over the following 5 days. This behaviour is typical of 20 events recorded over the past 8 years at this location.

Figure 4. Long term shear strain $\gamma_1$ measured at SJT for the 200 day intervals following the December 11/12 earthquake sequence in 1992, and the Loma Prieta earthquake on October 18, 1989. The two steps marked * in the upper trace correspond to Loma Prieta aftershocks.
Identify active faults, their geometry, their characteristics, and dates of past earthquakes.

The Sunklands, a swampy area along the St. Francis River in northeastern Arkansas, has been attributed to uplift across the river valley during the 1811-1812 New Madrid Earthquakes. Drilling in the lake has identified an organic mat, approximately 200 years old, beneath lake sediment. This mat was preserved by drowning surface organics following landsurface deformation that dammed the river in 1811-1812. Two additional organic mats, separated by lake sediment, occur in the area of maximum subsidence. Dates on the organics suggest that there have been at least two and possibly three earthquakes of sufficient magnitude to have caused total deformation of 2.5 meters in less than 8,000 years.
Research Quality Seismicity Data For Earthquake Prediction Efforts in the United States

Award No. 1434-93-G-2346
Program Element 11.2
Annual Technical Report

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INTRODUCTION

Seismicity catalogs represent the results of a multitude of incredibly complex data collection and processing steps. Changes in the systems used in these steps are unavoidable, as are the effects of those changes on the catalogs. The goal of this project is to develop automatic techniques for examining seismicity catalogs and identifying the times of variations in them. Once the times of these changes are identified, the technique must provide an educated estimate of what the cause of the change might be. We have succeeded in creating a strong candidate for this technique and are now in the process of testing it on many real and synthetic catalogs. This technique will provide unprecedented understanding of observed seismicity rate variations in U.S. seismicity catalogs. This understanding will lead directly to important improvements in the quality and consistency of the data in those catalogs and allow them to be examined for possible earthquake precursors for the first time.

Specific tasks which we report on here include:
- A study of global seismicity rate variations.
- Techniques for identifying seismicity rate variations.
- Application of the techniques to many catalogs produced in the United States.
- Tests of those techniques using synthetic catalogs with known characteristics.

The major results achieved so far include:
- Observed global seismicity rate variations can largely be accounted for by systematic errors in magnitude estimates.
- An automated technique for identifying changes has been developed and applied to over 100 seismicity catalogs. Results from seven U.S. catalogs are listed in Table 1.
- The technique has been tested using synthetic catalogs with known changes. These tests indicate that we can detect magnitude shifts and detection changes of \( \pm 0.2 \) magnitude units and greater, and rate changes of about 25% and greater, with reasonable reliability.
GLOBAL SEISMICITY RATE VARIATIONS

Investigation: A common assumption in many seismological studies is that the estimates of some parameter improve steadily as larger and larger regions are averaged over to create the estimates. This reflects the belief that the averaging process takes care of local variations that are known to exist. In seismicity studies, this assumption can be tested by examining variations in global seismicity rates. This is, after all, the largest data set available.

Figure 1 shows the observed global seismicity rate (events / 30 days smoothed with a 1000 day window) for events with $m_b \geq 5.0$ listed in the ISC catalog as a solid line. The rates vary from 75 to 140 events / 30 days with a mean of 104, and are expressed as rate / mean rate in this Figure. The observation of a factor of two variation in the global seismicity rates is interesting in the context of the assumption mentioned above. It is clearly important to understand the cause of this change, but this understanding can not be achieved using only the information from one magnitude band. Two other sets of observations which help elucidate the cause are shown in Figure 1:

![Graph showing seismicity rate variations](image)

The vertical bars show the times of rate changes identified using our technique which have distributions in the magnitude domain which are consistent with systematic changes in the magnitudes in the global catalog. The signs of the changes are consistent with the observed changes in rates, i.e. magnitude increases lead to apparent increases in rates and visa versa.

The solid squares in Figure 1 show rate variations which are predicted on the basis of a comparison of the original ISC magnitudes with a revised set of magnitudes.
calculated by Lilwall and Neary (1986). The revised magnitudes were determine using station corrections which improves their temporal consistency. The differences between the original and the revised magnitudes provide an estimate of systematic errors which is independent of the seismicity rates. The variations in this difference as a function of time were converted to seismicity rate changes which are shown in Figure 1. It is clear that much of the observed variation in rates can be explained by these systematic errors.

**Results:** Two completely independent techniques have been used to examine global seismicity rate variations. Both indicate that the bulk of those variations can be explained by systematic errors in magnitude estimates.

**AN AUTOMATED PROCESS FOR IDENTIFYING CHANGES IN SEISMICITY CATALOGS**

**Investigation:** While some seismicity changes reported in the literature may be real, others may be artifacts caused by changes in the seismic network or methods used to compile the catalog. Two common artificial changes in seismic catalogs which may be misinterpreted as real are changes in detection threshold, such as may occur if stations are added or removed from a network; and systematic magnitude shifts, such as may occur if the methods, stations or personnel used to determine magnitudes change. Our goal here is to develop automated techniques for recognizing and determine the nature of such changes.

We use magnitude signatures which shows the distribution of an observed change in a large number of magnitude bands (Habermann 1987, 1991) for characterizing the nature of seismicity changes. Our application differs from past studies in that the magnitude signatures are created using adjacent fixed length time windows (e.g. window length 3 years, or 12 samples). These windows are slid through the catalog one sample at a time, yielding a z-statistic comparing the rates of events in the background and foreground periods for each magnitude band and time. Negative z-values indicate an increase in the number of events. Because different types of changes (rate changes, magnitude shifts, and changes in detection thresholds) affect different magnitude bands in different ways, each type of change has a characteristic pattern in this plot, a characteristic signature (Figure 2, dark circles).

At each time sample, a decision is made as to whether the magnitude signature reflects a notable change. For this study, we use two criteria to make this decision:

\[
\text{Avg}(|Z|) > Z_{\text{crit}} \\
|\text{Avg}(Z_{\text{left}})| - |\text{Avg}(Z_{\text{right}})| > Z_{\text{crit}}
\]

where \(\text{Avg}(|Z|)\) is the average of the absolute values of z for the magnitude signature; \(\text{Avg}(Z_{\text{left}})\) and \(\text{Avg}(Z_{\text{right}})\) are the average z-values for the left and right sides of the signature, respectively; and \(Z_{\text{crit}}\) was chosen at 2.0. If either of
these criteria are met, the time is noted. We are currently investigating other criteria which may improve our scheme for detecting catalog changes.

At each significant time, several comparison signatures are created to model the change. This is done by imposing some known change on the events in the background period and comparing the altered background to the original to create a comparison signature (Figure 2, crosses). Several such comparison signatures are created, representing a variety of rate changes, magnitude shifts, or changes in detection thresholds. The goodness of fit between the original and comparison (altered background) signatures is evaluated from the residual ratio (Eneva et al., 1993). The "best guess" for the cause of the change producing the original magnitude signature is taken as the change which produces the comparison signature with the best fit.

**Results:** We applied the analysis described above to seven regional U.S. catalogs (see Table: "Changes found in Selected Regional U.S. Catalogs"). For the purposes of this study, we limited each possible change to one of six types: a rate increase or decrease, a magnitude increase or decrease, or an increase or decrease in detection capabilities. The algorithm found changes in each of the catalogs; further, each of the six possible changes was found at least once.

While the fits of the comparison signatures for many of the observed changes were quite good, others were poor, suggesting the observed change was caused by something other than a single change of the type described above. These changes may be caused by combinations of detection changes, rate changes, or magnitude shifts; or they may result from changes not examined in this study (e.g. changes in b-values or magnitude "stretching").

**Synthetic Catalogs as a Tool for Investigating Catalog Heterogeneity**

**Investigation:** We created a series of synthetic earthquake catalogs with known changes to test the algorithm described above. To generate the catalogs we use a Poisson process, specifying a catalog length, a total number of events, a b-value, a maximum magnitude, a magnitude of detection $M_{DET}$ (below which no magnitudes are observed), a magnitude of completeness $M_{COM}$ (above which all magnitude earthquakes are recorded), and a detection probability for events in the range $M_{DET} \leq M \leq M_{COM}$. For this preliminary study, we used parameters and a detection probability function which resulted in synthetic catalogs with similar properties to the Central Mississippi Valley (SLU) catalog (see Table).

We imposed known changes on the synthetic catalogs. For this study we restricted these to rate changes, magnitude shifts, or changes in detection thresholds (simulated by altering $M_{DET}$ and $M_{COM}$). To measure how well the algorithm performed in recognizing these changes, we applied the following scoring system:

$$\text{SCORE} = f_{\text{HIT}} - f_{\text{FA}}$$
where $f_{\text{HIT}}$ is the fraction of imposed changes that are found, and $f_{\text{FA}}$ is the fraction of changes found by the algorithm which are false alarms. This score has a maximum value of +1.0 if all the imposed changes are found and there are no false alarms, and a minimum value of -1.0 if the only changes found are erroneous.

**Results:** We applied our methods to 2000 synthetic catalogs and obtained scores for rate changes, magnitude shifts, and rate decreases (Figure 3).

The results show that we can detect magnitude shifts and detection changes of ±0.2 magnitude units and greater, and rate changes of about 25% and greater, with reasonable reliability. Catalog changes of larger size produce nearly perfect scores, with virtually all the imposed changes recognized and very few false alarms. We expect these scores may improve as better criteria for detecting catalog changes are developed.

We also note that even with small catalog changes, the algorithm does an excellent job of determining the type of catalog change. For example, consider a change in detection threshold of only +0.1, for which we obtained a score of only 0.48 (Figure 3). The algorithm identified 65% of the imposed changes, and 17% of the changes it did find were false alarms. Even so, 95% of the real changes it found were correctly identified, i.e., they were recognized as detection decreases as opposed to detection increases, magnitude shifts, or rate changes. (Note that an increase in the magnitudes of detection and completeness represents a detection decrease). By the time the change in detection threshold is +0.2 magnitude units, 99% of the imposed changes found were correctly identified. Similar encouraging results were also obtained with magnitude shifts and rate changes.

**REFERENCES CITED**


Table 1. Changes found in Selected Regional U.S. Catalogs.

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<th>CATALOG CODE</th>
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Table 1. Description:
Start time = time of first sample in a period of significant change;
Peak Time = time of peak change;
End time = last sample in change period;
TYPE = type of change (DD Detection Decrease, DI Detection Increase, RD Rate Decrease, RI Rate Increase, MD Magnitude Decrease, MI Magnitude Increase)
SIZE = amount of change (size of change for rate changes and magnitude shifts; magnitudes affected for detection changes). Only the single best-fitting change is shown. A question mark indicates a poor fit, suggesting something other than a simple detection change, rate change or magnitude shift; e.g. a combination of two or more changes.

<table>
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Figure 2: Magnitude Signatures for 3 Changes

- Original
- Altered Background

**Rate Increase 50%**
Fit: 0.109

**Magnitude Incr. +0.2**
Fit: 0.228

**Detection Decr. M < 2.2**
Fit: 0.174
Figure 3: Scores obtained (see text)

Rate Change (Factor Decrease)

Magnitude Shift

Change in Detection Threshold
Background

Widespread Holocene-age earthquake-induced liquefaction centered in the Wabash River Valley of southwestern Indiana and southeastern Illinois was first documented in 1990 by Obermeier et al. (1991). Subsequent systematic investigations of exposed river cutbanks and sand and gravel quarry walls of the Wabash River valley and major tributaries in Indiana were undertaken in 1991 and 1992 (Munson et al., 1992; Obermeier et al, 1992a; 1992b). Bank surveys ranged in distances from 150 to 210 km from Vincennes, Indiana, but paleoliquefaction features were not found beyond a radius of about 140 km from Vincennes. Combined, these investigations documented a total of 63 liquefaction sites with at least 196 paleoliquefaction features (dikes, sills and buried sand-blows), determined dikes decrease in size and frequency with distance from the Vincennes area, and estimated by radiocarbon dating, archaeological dating and stratigraphic correlations that paleoliquefaction features were the result of one or more very strong earthquakes centered in the Vincennes area. Most features were linked to at least one Middle Holocene earthquake. There is limited evidence for a second, late Holocene earthquake.

Paleoliquefaction features were also identified by Obermeier between 1991 and 1992 in bank surveys of segments of river valleys tributary to the Wabash River Valley in southeastern Illinois and the Kaskaskia River Valley, within x km of Vincennes (Obermeier et al., 1992b). He documented 39 liquefaction sites exhibiting a total of at least 88 paleoliquefaction features. Su and Follmer (1992; 1993) subsequently obtained radiocarbon ages that post-date liquefaction features at one site and both pre- and post-date a feature at a second site. Radiocarbon ages were on bulk soil materials.

Based on the extensive evidence of prehistoric earthquake liquefaction in southwestern Indiana and the initial findings in southeastern Illinois, we applied for and were awarded a USGS NEHRP grant to systematically determine the distribution, size and type of earthquake-induced paleoliquefaction features in southeastern Illinois valleys (extensive reaches of the Embarras River, Little Wabash River, Saline River and middle Kaskaskia River valleys). Additionally, the research was designed to begin to generate assessments of the age(s) of the liquefaction features, by means of integrated radiocarbon dating, archaeological dating, and stratigraphic and geomorphic analyses of Holocene alluvium, for comparison with the timing of liquefaction in southwestern Indiana.
1993 Research

The project began in the late Spring of 1993. Paleoliquefaction sites and their contexts were examined in Indiana guided by P. Munson (Indiana University) and Obermeier (USGS) and in Illinois on several occasions guided by Obermeier. Boat access areas were identified and simultaneously river reaches were spot-checked for eroding cutbanks. Unfortunately, river survey was severely curtailed during the summer and fall by record rainfalls and flooding caused by repeated heavy rains, discharge from filled reservoirs, and persistent high waters on mainstem rivers.

Nevertheless, systematic survey of eroding cutbanks by boat or foot was conducted along at least some reaches of all rivers except the Saline River. A total of 63 river-km were surveyed. 5 paleoliquefaction sites were discovered with a total of at least 13 liquefaction features. Along the Kaskaskia, 8 sites (not mapped on Figure 1) were discovered that had vertical sand and gravel filled features in diamicton that was overlain and in at least some cases underlain by sand and gravel in terrace landscape positions. Although some of the features have connections to overlying and underlying sand, including one apparent blow, it is still open to question whether these older features are liquefaction caused by earthquakes. Bank surveys additionally resulted in the discovery of four buried and surface archaeological sites and paleosols in stratigraphic contexts related to liquefaction features. A six-month no-cost extension has been applied for to complete the systematic bank survey.

Preliminary re-examination of 19 paleoliquefaction sites previously identified by Obermeier in 1991 - 1992 resulted in the discovery of an additional 12 surface and buried archaeological sites, 8 of which contained debris of known ages, 9 radiocarbon samples, and paleosols. Three of these sites were given more extensive attention. Two of them yielded radiocarbon samples for which ages are pending. At one site, one radiocarbon sample pre-dates liquefaction and a second sample is approximately penecontemporaneous with liquefaction. At the second site, several radiocarbon samples post-date liquefaction. We were unable to identify the liquefaction features at a number of these previously discovered sites, in some instances due to bank slumping but often due to high water. However, re-examination also resulted in the discovery of 5 additional liquefaction features at known sites. Combined with Obermeiers results, there are to date a total of 44 identified paleoliquefaction sites in southeastern Illinois valleys with 101 liquefaction features (Figure 1).

Geomorphic mapping of valley surfaces was conducted as part of the research program to further aid in establishing the age and context of paleoliquefaction features through cross-cutting relationships and the eventual analysis of landform-sediment assemblages and stratigraphy. Although mapping is incomplete, preliminary results indicate the presence of at least 6 geomorphic map units. From oldest to youngest these are 1) late Wisconsin sandy terraces, 2) late Wisconsin slackwater terraces in lower reaches of valleys that upstream are tentatively identified as becoming progressively more deeply buried, 3) relatively large-scale, filled, valley wall meanders that in places may be rock cored, 4) relatively featureless flood plain areas that at least in some areas appear as a low terrace, 5) in some cases multiple paleomeander belts, and 6) modern meander belt.

Stratigraphic descriptions of surficial sediments at liquefaction sites and other cutbanks below Holocene geomorphic surfaces indicates comparable alluvial facies among the valleys. Channel sand and gravel facies occurs slightly below normal low water level and underlies about 3 to 7 m of overbank silt facies that ranges from sandy to clayey (sandy loam to silty clay loam). The saturated sand and gravel facies serves as the source bed for liquefaction features. Well logs indicate this facies rests on bedrock, Wisconsin diamicton, or, beyond the Wisconsin glacial
limit, Illinoian diamicton and can be several decimeters thick. Basal portions of the silt facies consist of thin plane beds that often are internally massive and unoxidized or deoxidized in appearance. Differing degrees of pedogenic alteration obscure original sedimentary structures in the deoxidized to oxidized upper portions of sections. Multiple moderately to weakly expressed paleosols are common. A second silt facies, with comparable textural variability, occurs filling paleochannels cut into varying thicknesses of the first silt facies and sometimes the sand and gravel facies. Relatively earlier and later paleochannels are generally cut deeper than channels of intermediate age. Dikes are often truncated by these paleochannels. The associated silt facies commonly has a slightly coarser (sandy loam to loamy sand) base that locally exhibits thin cross-beds that rapidly fine upward to thin plane-bedded and laminated silt (silt loam) and finally pedogenically altered silt (silt loam to silty clay loam). The lithofacies assemblage and relationships to the water table are not unlike that of southwestern Indiana and is conducive to formation of earthquake-induced liquefaction.

A map of previously recorded archaeological sites in the project valleys was produced from the Illinois Archaeological Survey state site file. As geomorphic mapping is completed, sites with temporally diagnostic artifacts are being superimposed on the geomorphic base to provide at least minimum ages for stabilization of geomorphic surfaces. Unfortunately, in many areas Historic alluvium apparently buries the pre-Euroamerican settlement surface and any associated prehistoric cultural deposits. However, archaeological evidence to date tentatively suggests at least parts of the relatively featureless flood plain and low terrace stabilized by about 3000 B.P., at least parts of paleomeander belts stabilized or were abandoned by about 1200 B.P., and at least parts of the Historic meander belts stabilized or were abandoned by the early 20th century. A radiocarbon age of 7560 B.P. that pre-dates and an age of 4818 B.P. that post-dates one liquefaction feature (Su and Follmer, 1993) comes from fill in one of the relatively large-scale meanders. The latter age is about a meter below land surface. The ages indicate abandonment as an active channel prior to about 7600 B.P. and cessation of meander infilling shortly after about 4800 B.P. and after liquefaction.

Results and Preliminary Interpretations

To date, four sites with at least one dike at least as wide as 15 cm occur within 125 km northwest of Vincennes, Indiana (Figure 1). A fifth dike at least as wide as 15 cm occurs within 165 km to the west of Vincennes. No dikes are wider than 36 cm. The remainder of dikes are less than 15 cm wide and nearly all of these are less than 5 cm. All liquefaction features fall within about 175 km of Vincennes, a distance that coincides with survey coverage to date and is about 35 km farther than the envelope from Vincennes of liquefaction sites in southwestern Indiana. Sites at distances beyond this envelope occur to the west along the Kaskaskia River in Clinton and Washington Counties. This group of sites has a greater site frequency per river-km than along other reaches investigated to date and includes one dike at 15.5 cm width. It is possible that the envelope of earthquake disturbance from the Vincennes epicentral area is not necessarily circular. Alternatively, it is possible some or all of these sites are related to a disturbance(s) with an epicentral area other than the Vincennes area. These possibilities will be addressed in part when conditions allow the survey to be completed. To date, there is no distribution data that contradicts interpretations of the Indiana group (Obermeier et al., 1992b; Munson et al., 1992).

At this time, archaeological, stratigraphic, and radiocarbon information does not contradict the likelihood that nearly all liquefaction features in southeastern Illinois were the result of one or possibly more middle Holocene earthquakes, as concluded by the Indiana group (Obermeier et al., 1992b; Munson et al., 1992). However, to date only two sites have radiocarbon ages, and none of the ages are penecontemporaneous with liquefaction features. Two of the sites have liquefaction features that appear less weathered than, or penetrate
sediments apparently less weathered than, the other sites suggesting the potential for a younger (late Holocene?) event. At least one site possibly has two generations of features suggesting multiple events. Several other features, clustered in the southeastern-most part of the state, show little degree of pedogenic alteration and may be the result of the 1811-12 New Madrid earthquakes. Furthermore, if the features that penetrate diamicton and in some cases portions of the overlying sand and gravel under late Wisconsin terraces prove to be liquefaction caused by an earthquake(s), then a second late-glacial earthquake is possible. These possibilities will be addressed in future research.

References Cited


Figure 1. Location of known paleoliquefaction sites, distribution of maximum dike size, and river reaches surveyed in southeast Illinois. Survey coverage and sites represent cumulative results to date of Obermeier et al. (1993) and this ongoing research, with the exception of sites discovered along the South Fork of the Saline River by S. Obermeier (USGS) in 1993 and sites in Illinois along the Wabash reported by Munson et al. (1992).
Introduction

This report summarizes progress to date on the second phase (FY 93) of a multi-year investigation of the late Quaternary paleoseismic history of the San Andreas Peninsula reach of the San Andreas Fault (SAF). The Phase I research during 1992 identified and evaluated sites along this reach of the fault that had potential for containing a decipherable and datable paleoseismic record. The Phase II research is currently focused on the most promising site, the head of an active alluvial fan cut by the fault on the Filoli Estate, which is located between Crystal Springs Reservoir and the Town of Woodside.

We have been assisted in the work by Kevin B. Clahan, a graduate student at San Jose State University, whose research and educational activities are being partially supported by funding under this contract. We are also working closely with the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory which is providing radiocarbon analyses without cost.

Progress to Date

We have prepared a geomorphic map of the site that shows the deeply incised channel of Spring Creek and the locations of our backhoe trenches with respect to the active trace of the SAF (see Figure 1). We have excavated 11 backhoe trenches: 5 normal to the fault trace and 6 more that are fault-parallel. Both walls of each trench have been cleaned, sampled, and logged at a scale of 1 inch to 1 meter. At the fault, both walls of the trench, and in 3 cases the floor of the trench, have been logged at a scale of 1 inch to 0.5 meter.
Thirty-four detrital charcoal samples from key horizons have been submitted for AMS and conventional radiocarbon analysis. Several dozen more samples have been collected and are being prepared for possible future radiocarbon analysis.

We have also conducted informal reviews and discussions of our preliminary findings at the trench site. These reviews have been attended by interested parties from the U.S. Geological Survey, San Francisco Water Department, Lawrence Livermore National Laboratory, local colleges and universities, Filoli Estate Educational Environmental Program docents, Town of Woodside officials, and local geologic consultants.

Results

The active trace of the SAF has been exposed in 5 of the backhoe trenches on the Filoli site. In all cases the active zone of faulting ranges between 0.5 and 3 meters in width. Fluvial deposits ranging from fine silt to coarse gravel are involved in faulting at each exposure. Similar fluvial deposits, including paleo-stream channel deposits have been exposed in the fault-parallel trenches. Most of the fluvial units have extensive detrital charcoal. Preliminary results from 34 radiocarbon analyses indicate that the alluvium exposed in the trenches ranges in age from about 250 to 2,200 years B.P.

The paleo-stream channel deposits, which at one time crossed the fault at high angles and have been subsequently offset by fault rupture, represent potential piercing lines from which slip rate(s) may be determined. The paleo-stream channel deposits are stratigraphically complex; we have preliminarily identified at least 3 possible piercing lines.

Future Work

All the backhoe trenches will be monumented for possible future re-excavation and backfilled prior to the coming rainy season, and a detailed topographic map of the site will be prepared. During the rainy season, we plan to: (1) formalize our trench logs and refine subsurface stratigraphy as necessary; (2) obtain additional radiocarbon analyses; (3) evaluate the results of the radiocarbon analyses and correlate subsurface units; (3) prepare a preliminary three-dimensional model of the site; and (4) make preliminary estimates of slip rate(s) based on correlative paleo-stream channels.

Based on our work to date at the Filoli site, we believe that there is a high probability of successfully determining late Quaternary slip rate(s), recurrence interval(s) of surface rupture events, and amount of displacement per event on the San Andreas fault at the site. Because of the complexity of the site, and depending on the results of the work outlined above, we may continue research at the Filoli site through next year (FY 94) as part of our proposed Phase III research, which is currently planned to focus on a site in Portola Valley south of the Filoli site, which has been recommended for funding.
SITE PLAN
San Andreas Fault Study
Filoli Center
Woodside, California
Project No. 1154.01
10/18/93

LEGEND
- Stream thalweg
- Top of slope
- Bottom of slope
- Slope inclination
- Landslide
- Headscarp
- Trench

Figure 1
INVESTIGATION OF STRUCTURAL DEFORMATION IN THE LAKE COUNTY UPLIFT AREA OF MISSOURI AND KENTUCKY USING HIGH-RESOLUTION SH-WAVE SEISMIC REFLECTION METHODS

1434-93-G-2361

Program Element II.1
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Kentucky Geological Survey
University of Kentucky
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Investigation

The relationship between geologic structure and recent seismicity is one of the most important topics of research related to seismic hazard evaluation in the New Madrid seismic zone (NMSZ). Determining the association of seismicity and structural deformation in the NMSZ is hindered by the presence of thick, water-saturated, unconsolidated sediments of the upper Mississippi embayment. The upward continuation of bedrock faults into the unconsolidated material is often masked by the inability of the soft sediments to propagate large fractures. This problem, along with erosional and depositional patterns associated with the Mississippi river, makes identification and age determination of near-surface faults difficult.

Seismic reflection methods have been used within the Mississippi embayment to determine the style, extent, and age of tectonic deformation. Although recent high-resolution P-wave (compressional wave) investigations have successfully imaged faults in the unconsolidated sediments (Schweig et al., 1992; Sexton et al., 1992; VanArsdale et al., 1992), "the critical Quaternary-to-Recent section could not be resolved (Johnston and Shedlock, 1992)." However, through the use of SH-wave (horizontally polarized shear-wave) reflection methods, deformation in this interval can be imaged.

The primary objective of the research is to collect high-resolution common-depth-point (CDP) SH-wave seismic reflection data across the Lake County uplift (LCU), a Quaternary deformational feature associated with active faulting and recent seismicity (Russ, 1982), through parts of southeastern Missouri and southwestern Kentucky. In association with work to be performed during 1994, the profiling will complete a shallow traverse across the central LCU, near the feature's widest point, and attempt to identify the nature and extent of near-surface deformation in the area. Figure 1 is a map of the LCU showing the locations of the profiles, as well as those that will be completed during 1994. With increased resolution gained through the use of SH-wave reflection techniques, the location and magnitude of near-surface deformation in the LCU can be more thoroughly documented, and additional details associating shallow structure and modern seismicity can be determined.

Preliminary Results

SH-wave reflection tests, using a sledge hammer and mass energy source (i.e., Hasbrouck, 1987), were performed during the spring and summer of 1993 in order to identify target reflections and determine field recording parameters for CDP profiling. Figure 2 presents
walkaway sections from sites in Missouri and Kentucky on which shallow reflections have been indicated (see Figure 1 for locations of test sites). Based on the log from a seismic borehole in the Madrid Bend area of Kentucky (VSAB on Figure 1), the strong reflections in the 375 to 400 ms range are believed to correlate with the top of a 20 m thick Quaternary gravel unit. The reflections from approximately 500 ms are believed to be from the top of the Eocene section at a depth of about 60 m. Because these strong reflections are present, as well as several shallower reflections (primarily on the Marston, Missouri, section), it is probable that imaging of geologic features within the Quaternary section (< 60 m deep) will be successful using SH-wave reflection methods.

References


Reports


Figure 1  Map of the Lake County uplift (from Russ, 1982) showing the locations of SH-wave seismic reflection profiles to be completed in 1993 and 1994, reflection test sites, and a borehole that was used for correlation purposes.
Figure 2  SH-wave walkaway tests and velocity-depth models for Marston, Missouri, and Madrid Bend, Kentucky, compared to a generalized log of the VSAB seismic borehole (see Figure 1 for locations). The shaded reflections are interpreted to represent the top and bottom of the basal Quaternary gravel.
Analysis of Earthquake Data from the Greater Los Angeles Basin and
Adjacent Offshore Area, Southern California

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INVESTIGATIONS

The goals of this project are: (1) seismotectonic analysis of earthquake data recorded by
the CIT/USGS, TERRAscope, and USC seismographic networks during the last 17 years
in southern California; (2) improve models of the velocity structure to obtain more accurate
earthquake locations including depth and to determine focal mechanisms; and (3) studies of
the earthquake potential and the detailed patterns of faulting along major faults in the
metropolitan area and adjacent regions.

The (Mw 6.1, 7.3, 6.2) 1992 Landers earthquakes that began on 23 April with the M6.1
1992 Joshua Tree preshock are the most substantial earthquake sequence to occur in the last
40 years in California. We have synthesized aftershock data from this sequence recorded
by the SCSN to provide a detailed three-dimensional picture of the deformation. The
results appear in three papers, one was published in Science, second was published in JGR
while the third is to appear in BSSA special volume (June 1994) on the Landers
earthquake.

RESULTS

The 1992 Landers Earthquake Sequence: Seismological Observations

The (Mw 6.1, 7.3, 6.2) 1992 Landers earthquakes began on April 23 with the M6.1
1992 Joshua Tree preshock and form the most substantial earthquake sequence to occur in
California in the last 40 years (Sieh et al., 1993). This sequence ruptured almost 100 km
of both surficial and concealed faults and caused aftershocks over an area 100 km wide by
180 km long (Hauksson et al., 1993). The faulting was predominantly strike slip and three
main events in the sequence had unilateral rupture to the north away from the San Andreas
fault (Figure 1). The Mw 6.1 Joshua Tree preshock at 33°N58' and 116°W19' on 0451 UT
April 23 was preceded by a tightly clustered foreshock sequence (M≤4.6) beginning 2
hours before the mainshock and followed by a large aftershock sequence with more than
6000 aftershocks. The aftershocks extended along a northerly trend from about 10 km
north of the San Andreas fault, northwest of Indio, to the east-striking Pinto Mountain
fault. The Mw 7.3 Landers mainshock occurred at 34°N13' and 116°W26' at 1158 UT,
June 28, 1992, and was preceded for 12 hours by 25 small M≤3 earthquakes at the
mainshock epicenter. The distribution of more than 20,000 aftershocks, analyzed in this
study, and short-period focal mechanisms illuminate a complex sequence of faulting. The
aftershocks extend 60 km to the north of the mainshock epicenter along a system of at least
five different surficial faults, and 40 km to the south, crossing the Pinto Mountain fault
through the Joshua Tree aftershock zone towards the San Andreas fault near Indio. The
rupture initiated in the depth range of 3-6 km, similar to previous M~5 earthquakes in the
region, although the maximum depth of aftershocks is about 15 km. The mainshock focal
mechanism showed right-lateral strike-slip faulting with a strike of N10°W on an almost
vertical fault. The rupture formed an arclike zone well defined by both surficial faulting
and aftershocks, with more westerly faulting to the north. This change in strike is
accomplished by jumping across dilational jogs connecting surficial faults with strikes
rotated progressively to the west. A 20-km-long linear cluster of aftershocks occurred 10-
20 km north of Barstow, or 30-40 km north of the end of the mainshock rupture. The
most prominent off-fault aftershock cluster occurred 30 km to the west of the Landers mainshock. The largest aftershock was within this cluster, the $M_w$6.2 Big Bear aftershock occurring at 34°N10' and 116°W49' at 1505 UT June 28. It exhibited left-lateral strike-slip faulting on a northeast striking and steeply dipping plane. The Big Bear aftershocks form a linear trend extending 20 km to the northeast with a scattered distribution to the north. The Landers mainshock occurred near the southernmost extent of the Eastern California Shear Zone, an 80-km-wide, more than 400-km-long zone of deformation. This zone extends into the Death Valley region and accommodates about 10 to 20% of the plate motion between the Pacific and North American plates. The Joshua Tree preshock, its aftershocks, and Landers aftershocks form a previously missing link that connects the Eastern California Shear Zone to the southern San Andreas fault.

State of Stress From Before and After the 1992 Landers Earthquake Sequence

12 Aug. 1993, Submit. to BSSA, Special issue on the 1992 Landers earthquake

The state of stress in the Eastern California Shear Zone (ECSZ) changed significantly because of the occurrence of the $M_w$6.1 1992 Joshua Tree and the $M_w$7.3 Landers earthquakes. To quantify this change, focal mechanisms data from the 1975 Galway Lake sequence, the 1979 Homestead Valley sequence, background seismicity 1981-1991, and the 1992 Landers sequence are inverted for the state of stress. In all cases the intermediate principal stress axis ($S_2$) remained vertical and changes in the state of stress consisted of variations in the trend of maximum and minimum principal stress axis ($S_1$ and $S_3$) and small variations in the value of the relative stress magnitudes ($\sigma$). In general the stress state in the ECSZ has $S_1$ trending east of north and $\sigma=0.4-0.6$ suggesting that the ECSZ is a moderate stress refractor and the style of faulting is transtensional (Figure 2).

South of the Pinto Mountain fault, in the region of the 1992 Joshua Tree earthquake, the stress state determined from the 1981-1991 background seismicity changed on 23 April and 28 June 1992. In the central zone the $S_1$ trend rotated from N14°±5°W to N28±5°W on 23 April and back again to N16°±5°W on 28 June. Thus the Landers mainshock in effect recharged some of the shear stress in the region of the $M_w$6.1 Joshua Tree earthquake.

Comparison of the state of stress before and after 28 June 1992 along the Landers mainshock rupture zone showed that the mainshock changed the stress. The $S_1$ trend rotated 7°-20° clockwise and became progressively more fault-normal from south to north. Along the Emerson-Camp Rock faults the change was so prominent that the focal mechanisms of aftershocks could not be fit by a single deviatoric stress tensor. The complex P and T axes distribution suggests that most of the uniform component of the applied shear stress along the northern part of the rupture zone may have been released in the mainshock. The San Bernardino Mountains region of the $M_w$6.2 Big Bear earthquake has a distinctively different state of stress, as compared to the Landers region, with $S_1$ trending N3°±5°W. This region did not show any significant change in the state of stress following the 1992 $M_w$6.2 Big Bear sequence.

PUBLICATIONS and REPORTS


Landers Earthquake Sequence
April – December 1992

Figure 1. Landers aftershock region showing all earthquakes recorded by the SCSN of $M \geq 4.0$ from April to December 1992, and major faults (dotted if inferred) from Jennings (1975). Heavy line represents surface rupture. Joshua Tree earthquakes (April 22- June 28) are enclosed by a dashed curve. Lower-hemisphere, first-motion focal mechanisms of the $M \geq 5$ events are also shown. CRF, Camp Rock fault; EF, Emerson fault; JVF, Johnson Valley fault; NFFZ, North Frontal fault zone; BMF, Burnt Mountain fault, EPF, Eureka Peak fault, HVF, Homestead Valley fault.
Figure 2. Summary of the $S_1$ trends in the eastern California shear zone and along the San Andreas fault zone. The $S_1$ trends labeled 1978-85 are from Jones (1988). The stars indicate the epicenters of the $M_w$6.1 Joshua Tree, $M_w$7.3 Landers, and the $M_w$6.2 Big Bear earthquakes. The geodetic strain data are from Savage et al., (1990). The different $S_1$ trends are labeled with the respective year (see also Table 1). The question mark across Emerson Camp Rock faults indicates that the deviatoric stress tensor could not be determined using the method of Michael (1984). In the Joshua Tree area each set of three $S_1$ trends are shown as 1981-1991 data (short dashes), 23 April to 27 June 1992 (long dashes), and 28 June to 31 December 1992 solid lines. CRF-Camp Rock fault.
Prediction Algorithms

9960-10060

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PROGRAM ELEMENT II

Investigations

A number of earthquake prediction algorithms have been developed by scientists at the International Institute for Mathematical Geophysics and Earthquake Prediction in Moscow. Their approach involves the application of methods of pattern recognition to seismicity catalogs and other geologic and geophysical data to estimate the location and time of future strong earthquakes. The goal of our investigations is to test these methods and assess their usefulness in the U. S. program of earthquake hazard reduction. One of the most interesting of these Russian algorithms is known as M8. This algorithm uses time varying patterns of seismicity data to make intermediate term predictions of future strong earthquakes. All earthquake prediction algorithms of this type are developed by testing their performance on catalogs of seismic data. The structure and parameters of the algorithms are adjusted until they achieve significant success in the prediction of past earthquakes. The only way to evaluate these algorithms is to make future predictions in carefully designed tests that remove all possibility of cheating or self deception. Three investigators, V. G. Kossobokov, J. H. Healy, and J. Dewey (USGS Golden) have designed a test for the M8 algorithm which we plan to run for five years making predictions of earthquakes with Magnitude 7.5 or greater. In this test the algorithm examines seismicity in 147 circles of investigation in the Circum Pacific Seismic zone. Each circle has a radius of 427 km. (fig. 1 table 1). The predictions are updated every six months and the algorithm declares times of increased probability in the circles with anomalous seismic activity.

Results

In the post prediction test for the period from January 1, 1985 to July 1, 1991 the algorithm predicted eight out of ten strong earthquakes that occurred in the circles of investigation. This is a statistically significant result when compared to a null hypothesis which randomly distributes warnings in the circles of investigation. In the forward prediction period starting on July 1, 1991 the algorithm predicted two out of four strong earthquakes which occurred in the circles of investigation. This is not a statistically significant result because of the small sample. We plan to continue the test to December 31, 1997.
Conclusions

In its present form the algorithm would not be very useful in a public warning system because of the large number of false alarms. We believe that the algorithm is detecting real changes in the patterns of seismicity. The algorithm appears to give a significant probability gain in predicting the time and location of future strong earthquakes. If this is true then it should be possible to improve the algorithm and an improved version of this algorithm, in conjunction with other data, may be useful in a public warning system.

Publications

Kossobokov, V. G. and Healy, J. H., Testing an Earthquake Prediction Algorithm, in Press

Healy, J. H., Kossobokov, V. G., and Dewey, J. W., A test to evaluate the earthquake prediction algorithm, M8, USGS open-file report 92-401
Table 1. M8 test results

- TIP: - no TIP
- successful prediction
- earthquake located in this circle
- blank: insufficient data

\[\begin{array}{cccc}
\text{K} & \text{O} & \text{D} & \text{O} \\
\text{n} & \text{o} & \text{O} & \text{D} \\
\text{n} & \text{x} & \text{O} & \text{D} \\
\end{array}\]
Fig. 1. The 147 circles of investigation cover all the most active regions in the Circum Pacific seismic belt. Circles where the M8 algorithm declared a warning on July 1, 1993 have darker shading.
Active seismic studies of volcanic systems

9930-01496
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Investigations

In the last few years, we established the software and communications to assemble recordings of distant earthquakes from up to 1500 short-period vertical-component stations across North America. With this very large aperture array, we are currently probing the deep structure of the Earth, investigating the crust and mantle beneath California, and examining the earthquake rupture process. The papers summarized below have been the result of this past year's effort.

Results


The papers above use a variety of regional array measurements to find the sharpness and lateral variation of fine structure in the upper mantle and near the core-mantle boundary.


These papers use array measurements to see heretofore unresolvable patterns in the physics of earthquakes.
Investigations Undertaken and Results

One of the main efforts of this project during 1993 was the establishment of continuous GPS monitoring across the Los Angeles Basin in cooperation with Caltech's TERRAscope project and the Scripps PGGA. Within the first several months of operation, we have resolved the secular deformation signal with better precision than it had been previously known (Fig. 1). This is fundamental information needed for determining earthquake hazards for Los Angeles, one of the important goals of the Southern California Earthquake Center (SCEC). A paper with Yehuda Bock is presently in preparation on this topic.

Another main effort of this project was the coordination of many peoples' efforts on geodetically determining the displacement field of the Landers earthquake (Fig. 2). This work led to a paper that has been submitted to the BSSA special issue on Landers (#4 in list below). Modeling of these data and the USGS trilateration data has been done (Fig. 3) and a paper with Shawn Larsen is in preparation on this topic as well.

In addition, we have continued other aspects of our monitoring work, including transfer of operations and upgrading of several creepmeters along the Coachella Valley segment of the San Andreas fault (in conjunction with Kerry Sieh at Caltech and Roger Bilham at Univ. of Colorado) and the following GPS surveying operations:

1) A re-survey of the southern San Andreas fault - crossing arrays (35 stations) at Indio, Thousand Palms Canyon, and Indian Avenue was performed in February with major assistance from Riverside County Survey Division.

2) The Inter-County 1993 survey (130 stations) was performed in conjunction with the Crustal Strain project, and with major assistance from Los Angeles, Orange, Riverside and San Bernardino County Survey Divisions, as well as Riverside Co. Flood Control, City of Los Angeles, and Metropolitan Water District.
Figure 1. Change in length component of the baseline between Palos Verdes (PVEP) and Jet Propulsion Lab (JPL1). These sites are at the south and north margins of the Los Angeles Basin, and the rate of shortening of this line represents roughly the rate of compression across the Los Angeles Basin. The rate we determine from the first several months of monitoring this line with continuous GPS is $4.9 \pm 0.2$ mm per year, a result that is consistent with and more precise than previous measurements of this line. This rate is important for calculating earthquake hazard for the metropolitan Los Angeles area, and these data indicate that we may be able to monitor any substantial changes in this rate through time from now on. The signal observed is thought to represent either strain accumulation or aseismic slip on deep portions of active faults in the region, such as the Elysian Park Thrust system.

Figure 2. Displacements of geodetic monuments in the vicinity of the 1992 Landers earthquake sequence (modified from Hudnut et al. - #4 in public. list). Stations are represented by triangles, displacements vectors by arrows, and the main event epicenter by a star.
Figure 3. Slip distribution for the main ruptures of the Landers earthquake sequence determined from geodetic data (Murray et al., 1993 - GRL and Hudnut et al. - #4 in public'n list). This result is for a 29 segment fault geometry using singular value decomposition inversion (37 singular values in this case), as presented at the 1993 Fall AGU meeting (Hudnut and Larsen, 1993). Contoured slip values are in meters, with one meter separation.
Reports Published (and submitted)


LANDSLIDES IN LAKE WASHINGTON, SEATTLE: COINCIDENCE INTRA-LAKE AND CORRELATION WITH REGIONAL SEISMIC EVENTS

The study of the drowned forests on landslides in Lake Washington, Seattle is reaching closure. The main hypothesis of simultaneous landslides and seismic triggering is considered established. Results crossdating the landslide trees for one site at south Mercer Island (SMI) with a tree 23 km away that was killed and buried in a tsunami deposit (Atwater and Moore, 1992) were published (Jacoby et al, 1992). These papers and companion papers established the likelihood of a major earthquake in Seattle about 1,000 years BP. Additional tree samples from the Kirkland slide at the north end of the Lake and from the west Mercer Island slide were collected in late 1992 and 1993. The samples were crossdated with the SMI trees. Results indicate the same year and season of death for the SMI trees and 5 of the 7 Kirkland samples (One tree died three years earlier and one was too decayed for analysis.) Nine samples were collected from West Mercer Island but only three had outer rings intact. All three crossdated with the SMI trees and again showed the same year and season of death (Jacoby et al. 1993). Two radiocarbon dates of wood samples from trees on the lake bottom give dates prior to the ca. 1000 years B.P. event and suggest that there may have been previous events. However, such trees are rare in our investigations of the lake bottom and it is difficult to tie them to a specific landslide. We do not plan further sampling unless SONAR and profiling surveys give us definitive target areas.

In May of 1992 we sampled old-aged Douglas fir [Pseudotsuga menziesii (Mirb.) Franco] on Vancouver Island in an attempt to develop an absolutely-dated, living tree chronology old enough to crossdate with the Lake Washington trees. This is the oldest stand of Douglas fir we have heard of in the region but they may be too far away from the Lake and in a somewhat different climatic regime. We
obtained samples extending back to 700 A. D., beyond the estimated radiocarbon date of about 1,000 A. D. for the Seattle event (Atwater and Moore, 1992 and Jacoby et al. 1992). These core samples were all dated and measured. The data are now being rechecked for dating accuracy and precision of measurements. Preliminary results did not yield a certain crossdate. The rechecked chronology of ring widths that we are now developing will be used for further attempts to absolutely date the tree samples from the Lake Washington landslides.

R. Bucknam, R. Schuster, A. Nelson, P. Pringle and F. Bauman, geologists or geological engineers working in the region are sending samples to the Tree-Ring Lab. from sites where there have been landslides or tsunami deposits that may be earthquake related. We are processing these samples and other samples we collected from the region. We will attempt to crossdate all the samples to determine relative timing of events near Seattle and along the coast from. This tree-ring investigation and dating will become part of another project that will be reported on in 1994.

References and Reports:


ABSOLUTE DATING OF PREHISTORIC EARTHQUAKES BY TREE-RING ANALYSIS IN CALIFORNIA

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Program Element II.5

1. San Andreas Fault north of San Francisco:

We have found possible evidence of the 1906 San Andreas fault earthquake in 10 of 14 living coast redwood \(\textit{Sequoia sempervirens}\) trees at Plantation Ranch. Plantation is a ranch just south of the primary study area. It is one of the few locations where uncut old-aged trees grow on and near the fault zone. We took increment cores from 14 trees near the fault and detected possible effects of the 1906 event in the rings of 10 of the trees. In five of the trees the effects are unequivocal. Two of the trees were unworkable due to decay or anomalous growth. We also found 1906 damage in a redwood tree on the Kelly-Thompson Strawberry Ranch near Watsonville, south of San Francisco. These analog results give us a guide for what effects to search for in the samples from old-aged trees in order to identify prehistoric earthquakes.

A large number of samples were taken in 1989 and 1991 from stumps and trees in our primary study area near Gualala, California, north of San Francisco. All of the time in 1993 was devoted to analysis of these samples. The most promising samples are from along the fault at two locations. At the first location the fault appears to be concentrated within a single, well-defined trace. A small creek drainage was offset approximately three times the estimated displacement of about 5 meters for this area due to the 1906 earthquake. Several samples of stumps from the offset creek site have been crossdated with the master chronology and living trees. The ring-width data from three dated trees show disturbances that might be due to earthquake movement of the fault. These dated disturbances are being compared to trees from a site a few kilometers to the northwest along the fault where we also obtained samples of excellent quality. The second set of samples is from a
recently-logged area where we were better able to discern the fault zone, sag ponds, and in echelon elongate depressions. We were able to obtain samples from trees at strategic locations where fault rupture was likely to have disturbed the trees. These samples from this second site are now being analyzed. We are also making additions to the undisturbed or master chronology for absolute dating of the fault-zone trees and comparison of normal growth with the times of disturbed trees. The tentative control and dating chronology extends from the present back to 361 AD. Oldest fault-zone trees analyzed to date now extend back to 1166 AD.

The results of the analog studies indicate that in addition to severe trauma, disturbance by earthquake accelerations and displacement can produce varying effects in the annual rings on different sides of the same tree. That is the ring widths can be diminished on one side and enlarged on the other. If several cores or radii are measured from one tree, the result of these types of disruption of the normal growth pattern is to increase the standard deviation of the ring widths for a few to many rings. In the extreme case growth rings can be missing on the damaged side of the tree. Insertion of zeros to account for the missing rings also increases the standard deviation for those years. The resulting time series of standard deviations for the ring-width indices for multiple cores from one tree or for several disturbed trees would show an unusually large standard deviation beginning at the time of disturbance. We are applying this type of evaluation to the data from both sites and other fault-zone trees.

2. Cascadia Subduction Zone (CSZ): Mad River Slough and Eel River:

We have now crossdated root portions from nine different trees submerged at Mad River Slough near the Mendocino Triple Junction at the southern end of the CSZ. This location is about 70 km north of the epicenter of the 1992 Cape Mendocino earthquake. One can see that the deaths or end of final cell formation took place over 4 growing seasons. Trees, having no central nervous system, often do not die all over at once. If growth hormones and carbohydrates reach a cambial site, with appropriate temperatures, cell division can persist until these substances are exhausted. Even within one tree there can be several years difference in when cell division stops at different parts of the tree. The closely-spaced death of these trees indicates a rapid subsidence event leading to their deaths.
Core samples from living trees at Agate Beach in Patrick Point State Park are dated and 5 cores from 2 of the trees extend back to 1647 or beyond. The oldest core dates back to 1549. Radiocarbon dates for the Mad River roots indicates the outer rings to be about 1700 A. D. We collected multiple cores from all the old living trees and have accounted for all of the missing rings. The multiple cores were necessary for crossdating within each tree. One can see rings pinching out even on a core only 5 mm across. Attempts to crossdate these trees with the Mad River roots have been unsuccessful so far although the Agate Beach trees do crossdate with their own roots. Agate Beach trees are being rechecked and further crossdating with the Mad River roots will be attempted.

Samples from roots of drowned trees (the trees are decayed away) at nearby Eel River are under analysis. Preliminary results indicate they are not the same age as the Mad River trees. We have 31 samples from 7 trees. At least half have outer rings that can be used to determine the last year/season of growth. The time of death will be determined relative to the Mad River "trees" and possible calendar year by crossdating with the Agate Beach living-tree chronology. The Eel River samples are of much better quality than the Mad River samples and have much less distortion in the rings. There are higher correlations between the ring-width variations of the Eel River roots. Tentative dating between the Eel river samples and Agate Beach trees suggests the Eel River trees may have died in the mid 1700's but more samples must be processed before this date should be given much credence. These sites are important parts of the larger question of major subduction zone earthquakes in the CSZ. Further tree-ring and radiocarbon analyses are underway by this project and others.

Reports:

Title: Quaternary deformation in response to subduction and triple junction migration, Crescent City, California: Project Number: 9460-11031

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Program Element: II. 1,4,5,

Investigations undertaken:

The uplift and subsidence history of coastal areas is a subject that intrigues many. Likewise, studies of coastal deformation along the Cascade forearc have been the subject of much recent work that contributes to arguments regarding the seismic potential of the forearc region.

The purpose of this study was to investigate the nature of Quaternary deformation associated with the Crescent City lowland which lies along the southern part of the Cascadia forearc. This work has been carried out in a collaborative effort with Sam Clarke, project chief who is investigating offshore structures using seismic reflection profiling.

The investigation included 1.) developing topographic surface models in ARC-INFO from 1:24,000 DEM's which can be used to show the geomorphic expression of Quaternary deformation, 2.) collecting fracture orientation and kinematic data to establish dominant structural orientation and fault style, 3.) measuring vertical displacement of Quaternary wavecut surfaces, 4.) collecting and submitting material for radiocarbon dating of Quaternary horizons that are critical for determining displacements, and 5.) collecting oriented samples from late Neogene and Quaternary strata for magnetostratigraphy and evaluation of block rotations.

Previous work

Marine deposits of late Cenozoic age in the Crescent City area record a history of slow emergence of the land surface (Diller, 1902). Recent work in the forearc region north and south of Crescent City, in the Humboldt Bay region (Carver, 1987; Clarke; 1992) and in the Coos Bay region by (Kelsey, 1990; McInelly and Kelsey, 1990; Muhs, 1990), have been pioneering in their efforts to constrain deformation rates, locate active structures and establish the deformation mechanisms in this region.

The salient structural features at the Crescent City lowland noted by previous workers include 320° trending north and south edges to the platform which are inferred to be fold and fault controlled (Back, 1957; Maxson, 1933), the north-south striking range front which forms the
eastern edge of the platform is also inferred to be fault controlled, and the gently northeast tilt of the Pliocene sedimentary rocks which are inferred to overlie the backlimb of a southward verging thrust (Clarke, 1992).

RESULTS
Quaternary deformation
Quaternary deformation has occurred along high-angle faults that cut the Plio-Pleistocene-Quaternary Battery Formation (Back, 1957) and may also cut late Pleistocene(?) eolian deposits near Point St. George. The wavecut erosional surface that underlies the Battery formation is noticeably warped west of a high-angle, 040° trending reverse fault which offsets the erosion surface and forms the contact between Jurassic-Cretaceous Franciscan assemblage and Point St George Formation (Back, 1957).

Warping of the Quaternary surface appears to be longer wavelength subparallel to the 320° trending low-angle thrusts and shorter wavelength subparallel to the 040° trending high-angle reverse faults.

A minimum estimate of deformation can be had by inferring that the wave-cut surface that underlies the Crescent City platform represents the last high sea level stand (125 k.a.b.p.) which was six meters above present (Chappell, 1983). This surface is noticeably irregular and cut by faults in at least three locations. The broadly warped surface ranges in elevation from 2 to 8m with a separation across one fault of approximately 5-6 meters, and minimum of 2 meters across a second.

Fracture trends in Neogene sedimentary rocks
Gently northeast-dipping (~30°) thrust faults that trend 320° were found cutting latest Miocene and Pliocene strata of the St. George Formation west of Crescent City. The strata are gently northeast tilted 10 to 20 degrees, the morphologic surface that overlies them is also inclined suggesting minimum tilt rates of 2°-7°/m.y. Geomorphic response to the tilting suggests that the deformation is ongoing, albeit slowly. The thrust faults, which are exposed in beach cliffs, show a small amount of offset on the order of 0.5 to 1.0 m. The thrusts cut 020°-030° trending normal faults which are very common and may be slightly older, possibly syntectonic with deposition of the St. George Formation. The thrusts exposed onland are inferred to be small splays from a much larger structure which lies just offshore, and has strong morphologic expression and possibly a submarine scarp. Locally the thrusts terminate laterally into high-angle lateral-ramps which appear to reactivate the 020°-030° trending structures.
Geomorphology

Crescent City Platform

The Crescent City Platform is a prominent lowland that averages about 12 m in elevation and slopes gently to a sharp prominent range front at about 60 m elevation. The range front climbs steeply to about 120-180m. The ranges are deeply dissected but typically flat-topped where remnants of an older paleo-surface, as well as shallow marine and fluvial deposits are preserved (Diller, 1902; Stone, 1992). The platform is about 7 miles wide at its greatest width and about 20 miles long. It terminates to the north where is bound by a 320 trending abrupt, steep range front. The platform terminates to the south initially along a 320 trending shoreline to the west and then tapers southward to the present sea cliff.

Although there is little relief on the platform, the ridges and drainages, as well as broader swells and lows commonly have a strongly preferred orientation that is lattice-like and geometric. Within a mile of the coast the topography is strongly controlled by the dune orientation which reflects the prevailing wind direction. The dune orientation has coincidentally formed in a northwesterly direction that is subparallel to one of the dominant structural trends.

Indications of paleoseismic activity

The Petrolia 7.1 magnitude earthquake caused coseismic uplift along the coast near Cape Mendocino and Punta Gorda. The uplift was on the order of magnitude of about a meter near the coast. It was evident nearshore that numerous benches with 0.5-1.5 meter steps were preserved on the broader wavecut platforms, and the speculation arose that these features may represent the result of previous paleoseismic events. Thus, an effort has been made to identify the more subtle steps and related features along the coast that may have formed in response to sudden but small uplift; the following features have been identified.

Pholad horizons

Pholad boring that infrequently contain fossil remains are found in two distinct settings along coastal exposures between Crescent City and Point St. George. The older erosional surface with pholad borings underlies the Battery formation and is developed on several different rock types including Franciscan radiolarian chert, graywacke and siltstone of the Mio-Pliocene strata. This horizon is inferred to be Pleistocene in age. The other occurrence of pholad borings is on wavecut surfaces that lie within the upper intertidal zone, above the modern beach deposits. Flatly planed surfaces developed on gently inclined strata suggest a wave dominated abrasional process formed the surface. Such surfaces that presently lie within the upper intertidal region, are covered by sessile organisms.
indicating that the surfaces are not presently being abraded and have been elevated out of the sand dominated part of the swash zone.

Boulder benches
Some erosional surfaces appear to have been elevated just above the present day high-tide and storms level. In places these wavecut surfaces are covered by boulder beds, and the boulders, likewise show evidence of a upper flat, presumably wave abraded surface that has been abandoned suggesting step-like incremental emergence. The magnitude of relief between these remnant surfaces, and similar wavecut notches is 0.75 to 1.5 m. Locally four such surfaces have been identified within seven meters of relief along the shoreline. There is no age control on these morphologic features as yet.

Liquifaction features
Dewatering structures which produced convolute bedding and mushroom shaped folds in horizontally bedded nearshore facies sediments were only observed at one location north of the Crescent City platform. Flattened pebbles which ordinarily lie within the bedding plane or at a low angle to bedding were likewise rotated to steep and vertical angles near release pipes within the section. The horizon characterized by dewatering structures lies approximately 2 meters above a wavecut unconformity on Franciscan basement that lies about 2 meters above sea level.

Stranded shelly beach deposits
A mappable horizon of shelly beach lag deposits is located behind the first dune ridge above the winter high-tide level along the northwestern edge of the Crescent City platform. The presence of this deposit may indicate a recent regression of the coast. Shell material has been collected and submitted for radiocarbon dating to establish the timing of this event.

Conclusions
The Battery Formation and it's underlying unconformity have been faulted indicating some Quaternary faulting has occurred near the surface. Subtle geomorphic features on the platform coincide with the location of Quaternary faults exposed along the coast suggesting some modification of the surface by faulting and also by broad warping. Subtle features along the coast and in the nearshore area suggest modest incremental elevation changes relative to present day sealevel. We await the results of radiocarbon dating to help constrain the timing of these features and possible displacement rates.
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Instrument Development and Quality Control

9930-01726

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Investigations

This project supports other projects in the Office of Earthquakes, Volcanoes and Engineering by designing and developing new instrumentation and by evaluating and improving existing equipment in order to maintain high quality in the data acquired by the Office. Tasks undertaken during this period include construction and testing of digital seismic telemetry units, building a portable seismic alarm system and maintaining the Seismic Group Recorder system, among other things.

Results

Construction and testing of 20 digital seismic telemetry (DST) field stations has been completed. Four units have been deployed in the San Francisco Bay area and have been telemetering 16-bit seismic data via radio and microwave links to Menlo Park. Another unit has been operating from Mt. Spurr in Alaska telemetering its data 400 miles via radio and telephone lines to Fairbanks. A dozen units are being readied for deployment in Hawaii.

A system to replace the RTP, dubbed Earthworm, is under development. This project has been providing support services for the Earthworm development, including building special circuits needed as accessories to the A/D. A digital seismic system from Nanometrics was received. Consisting of eight 24-bit digitizers and a central receiving computer, it will be installed as the southern half of the Hayward Fault seismic experiment. The system has been undergoing in-house testing and is awaiting high-speed telemetry radios for field installation. A portable version of an Early Warning Seismic Alarm system that was developed and tested following the Loma Prieta earthquake has been constructed. This will allow us to rapidly install an early warning system following a large earthquake at any location. The system will then radio a warning of aftershocks to vulnerable areas (such as rescue work sites) located some distance from the epicenter.

The 190-unit Seismic Group Recorders have been active this year. They were used in seismic refraction experiments in the San Francisco Bay area, Nevada, Canada, the California north coast, the southern Sierra Nevada and New Mexico. This project supported most of these operations with instrument maintenance, enhancement and field support.
Piñon Flat Observatory:
Studies in Crustal Deformation Measurement and Interpretation

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This grant provides support for research on crustal deformation, including collaborative studies with USGS-sponsored investigators doing research at or near Piñon Flat Observatory (PFO); as will be evident from the rest of this report, our studies have extended well beyond this location.

Crustal Strain Rates in Southern California

During the past year we have completed a study of the current rates of interseismic deformation in southern California; this has been accepted for publication in the *Journal of Geophysical Research*. We have used the trilateration data collected by the USGS over the 18-year period from 1973 through 1991. The southern California trilateration networks consist of approximately 100 geodetic stations distributed across the major faults of this area. The distances between adjacent stations were measured on a yearly basis to a precision of about 0.2 ppm. Over the distances of interest here (5 to 40 km), this precision is comparable to that attained by current GPS measurements.

Here we present only one interesting and unexpected result of this work. Figure 1 shows the variability of strain accumulation along the length of the San Jacinto Fault in southern California. Each of the plotted results shows the average yearly amount of shear-strain accumulation in a small sub-network of four adjacent trilateration stations. By dividing the entire network into smaller sub-networks we are able to determine the spatial variability of crustal strain accumulation over the 18-year span of these measurements. The majority of these results show between 0.2 and 0.4 μrad yr⁻¹ of shear strain accumulation, in good agreement with the expected rate of about 0.3 μrad yr⁻¹ (based on 10 mm yr⁻¹ of interseismic slip below about a 10 km locking depth and a fault-perpendicular averaging-width of 20 km for the geometry of the trilateration networks). There is, however, a cluster of results from six of the sub-networks which show significantly larger shear strain rates—in fact, the deformation of these networks is larger than any others in the entire southern California area, including networks which monitor the San Andreas Fault. All of these sub-networks are located in the Borrego Mountain Badlands along the San Jacinto Fault as it enters the Imperial Valley.

We believe there are several forces at play which have combined to produce these very large strain rates. The lower panel of Figure 1 shows the seismicity along the San Jacinto Fault from the Caltech/USGS catalog. One of the most obvious differences along strike is that the maximum depth of seismicity becomes progressively shallower toward the right (southeast) in the figure. Other researchers have attributed this to the increase in heat flow toward the Imperial Valley region and have suggested that isotherms in the crust should be closer to the surface as a result. This implies that the depth below which steady interseismic slipping occurs also becomes shallower toward the southeast.
A consequence is that the resulting crustal deformation will be more concentrated near the surface fault trace, thus producing higher shear strain estimates in the nearby sub-networks. To produce the 50% higher estimates would require about a 50% shallower locking depth in the Imperial Valley region compared to farther northwest along the fault. The seismicity suggests this might be reasonable, but it would be very difficult to explain the other nearby strain rate results which are back down in the 0.2 to 0.4 \( \mu \)rad yr\(^{-1}\) range.

Another possible explanation for this shear strain discrepancy is a larger amount of deep interseismic slip on the Borrego Badlands segment of the San Jacinto Fault: a 50% higher slip rate would produce 50% higher shear strain rates in this area. Again, the difficulty is to explain the lower strain rate results nearby. It is difficult to imagine that a relatively short section of the San Jacinto Fault can average 50% more slip over an 18 year period compared to neighboring segments.

Finally, we note that the location of the surface rupture for the 1968 Borrego Mountain earthquake coincides remarkably well with the location of the anomalously high shear strain results. The rupture location is plotted on each panel in Figure 1. Some theories of the earthquake cycle predict accelerated strain accumulation following a large event as a result of the interaction between the viscoelastic lower crust and the elastic upper crust in the vicinity of the earthquake. Thatcher (JGR 88, 5893-5902, 1983) determined a time constant of about 30 years for this effect from long-term geodetic data near the San Andreas Fault in California. If these large strain rates are a result of this effect we would expect to see a slowing down of this deformation over the 18 year period of measurements. In fact, the trilateration data from this part of the network are well explained by a linear accumulation of deformation. While these data cannot distinguish between a steady accumulation of deformation and an exponentially decaying accumulation with a relatively long time constant, this time constant would have to be significantly longer than the 30 years suggested by Thatcher for the San Andreas Fault.

At this point we cannot definitely say what is causing these large strain rates; while a combination of the possibilities suggested above is likely, to understand the problem more fully will require further geodetic measurements in the area.

Deeply Anchored Geodetic Monuments at Parkfield, California

Another project completed in the last few months was to construct two deeply-anchored geodetic monuments at Parkfield, California, to supplement the USGS two-color EDM monitoring program there. This came about as a result of our instrument development work at PFO (largely accomplished under USGS sponsorship). The very high sensitivity of the strainmeters and tiltmeters deployed at this site required us to understand the issues involved with monument stability well before the current needs developed from multi-wavelength EDM and GPS geodesy. Over the past several years we have designed and installed ultra-stable monuments for several permanent GPS marks in southern California, as well as for other geodetic points around PFO. The extension to Parkfield was not planned in our original proposal, but was made possible by the funds “freed” by the UC-system cut to our salaries.

The Parkfield two-color EDM network has been monitored since 1985 on a schedule of about three times per week. The network consists of a central station near the San Andreas Fault with remote stations located at a variety of azimuths, with about half of them crossing the fault. After a few years worth of measurements it became apparent that some of the line lengths showed a conspicuous yearly signal, probably caused by the motion of the remote reflectors. Each of these reflectors is set on a steel pier buried about 1.7 meters into the ground, with the upper 0.5 meter isolated from the surrounding soil. Figure 2 shows a scaled side view of this arrangement (as well as of one of our alternative marks). These monuments are especially susceptible tilt and displacement because of water
penetration and absorption into the clayey soil. These effects appear to be especially large at the sites POMO and MIDE, where we have installed our auxiliary marks, because of the rugged topography on Middle Mountain. During the rainy season the soil near the surface swells and forces the existing monument at MIDE to begin moving away from the central station. As the clay dries out in the summer months the movement is then back towards the central station; the total amplitude of this motion being about 10 mm. POMO shows similar behavior, with opposite sign.

In September 1993 we built ultra-stable auxiliary marks at these sites, and reflectors were installed on them by Dr. Langbein. Each of these marks consists of a total of five galvanized pipes sunk 10 meters into the ground—one vertical pipe and four inclined pipes at 90 degree increments (Figure 2). The five pipes are welded together at their common intersection point roughly 1.5 meters above the ground. Not only do these monuments extend much deeper than the older ones, but the lateral bracing afforded by the four inclined pipes make them very resistant to any vertical or lateral near-surface stresses. To reduce the coupling between the surface soil and the support pipes, each pipe is wrapped with a thick layer of compliant foam (commercial pipe insulation) from the surface down to about three meters; thus the top three meters of ground can swell and contract without affecting the position of the EDM reflector, which is located just above the intersection point.

Since the beginning of October the distances to these two new reflector sites have been measured along with the previously existing sites. There is not yet enough data to understand how well the new marks will reduce the seasonal signals seen on the older style monuments, but we expect that an answer will be evident soon, as the rainy season is just beginning.

Additional Projects

The projects described above are complete (except for examining the data collected by Dr. Langbein at Parkfield); we describe here projects that are currently underway.

- **Sources of postseismic crustal motion:** We will continue our analysis of the data collected at PFO before and after the Landers earthquake, which show deformations unprecedented in the history of the observatory. We are currently investigating possible sources for the postseismic signal, the most likely of which appears to be aseismic fault slippage occurring in different proportions (and perhaps at different locations) than the seismic part of the rupture did—a result of great importance to understanding the stress changes imposed by this earthquake. Another possibility is widespread crustal relaxation in response to the stress changes imposed by the faulting; we will be attempting to model this and compare it with PFO data and the GPS data collected by UCLA.

- **Detection of anomalous deformations:** Guided by our studies of the Landers postseismic signal, we will investigate how various types of deformation data can be applied to determine, or at least bound, possible aseismic fault motions: the goal being to produce a system for deducing, from the data available, whether some kind of anomalous motion has occurred.

- **Fault-scale GPS:** We are continuing a study on the accuracy of GPS measurements at short (<20 km) distances, by analyzing data from a 14-km continuously-monitored line set up in mid-1990; we hope, during 1994, to relocate this line to have a length of 4-5 km to determine how errors are reduced by this change in length. With this kind of data we are not limited to estimating just the short-term or long-term scatter, but can find the true error spectrum, thus providing needed guidelines for fault-scale GPS studies.
Cooperative investigations: We will continue our cooperative studies with investigators working at PFO under the sponsorship of the U.S. Geological Survey NEHRP, on developing, comparing, and evaluating improved methods for measuring ground deformations for periods from seconds to years. This includes comparisons of geodetic techniques (such as two-color EDM and GPS), as well as studies of strainmeters and tiltmeters.
Fault Parallel Shear–Strain–Rate For Networks on SJF

Figure 2

Parkfield Two-Color EDM Monuments

Existing

Deeply Anchored

10 m

1.7 m

Enlarged Top View
Deeply Anchored

1 meter
TILT, STRAIN, AND MAGNETIC FIELD MEASUREMENTS

9960-10146, 9960-11146, 996012146

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PROGRAM ELEMENT II

Investigations

1. To investigate the mechanics of failure of crustal materials using data from both deep borehole tensor and dilational strainmeters and near surface strainmeters, tiltmeters, and arrays of absolute magnetometers.

2. To develop physical models of incipient failure of the earth's crust by analysis of real-time records from these instruments and other available data.

Results

1. BOREHOLE STRAIN ARRAY IN CALIFORNIA

A network of 23 borehole strainmeters along the San Andreas fault zone and in the Long Valley Caldera continues to be monitored and maintained (Figure 1). All instruments are installed at depths between 117-m and 324-m and all are between 1-km and 5-km from the surface trace of the fault. High frequency dilatometer data in the frequency range 0.005 Hz to 100 Hz are recorded on 16-bit digital recorders with least count noise less than $10^{-11}$. Low frequency data from zero frequency to 0.002 Hz are transmitted through the GOES satellite to Menlo Park, CA, using a 16-bit digital telemetry system. At the USGS in Menlo Park the data are displayed in "almost real time" and are continuously monitored with detection algorithms for unusual behavior. Least-count noise is about $5*10^{-12}$ for the on-site digital recordings, and about $2*10^{-11}$ for the satellite telemetry channels. Earth strain tides, strain transients related to fault creep and numerous strain seismograms from local and teleseismic earthquakes with magnitudes between -1 and 6 have been recorded on these instruments. Static moments and total earthquake moments are determined from the coseismic strains and total strain changes observed with the larger events.


A moderate sized slow earthquake was recorded on a small network of three borehole strainmeters near San Juan Bautista, California, from December 10 to December 15, 1992. This event had an associated earthquake swarm, an "aftershock" sequence and 3.7 mm of surface creep several days later. Fault parallel shear and dilatational strain changes of 1.1 microstrain and 0.1 microstrain were observed starting about 0700 UT on a borehole tensor strainmeter installed about 1.2 km from the San Andreas fault near San Juan Bautista while dilatational strains of 0.65 microstrain and 0.15 microstrain were observed on two borehole dilatometers, five kilometers to the northwest at distances of about 1 km and 7 km from the San Andreas fault starting at about 0730 UT on December 11, 1992. (See Figure 2). Three magnitude 3 events occurred at 0512, 0729, and 0804 on December 11 and these were followed by two
magnitude 3.7 and numerous smaller events from 1553 UT on December 12. (See Figure 3). These seismic events form an approximate donut shape with a diameter of about 5 km from 3 km to 8 km beneath the strainmeters. Surface creep started late on December 14 and continued until December 18. Initial quasi-static modeling indicates aseismic moment release for the event was about $10^{16}$ Nm, equivalent to a magnitude 4.7 earthquake. The total moment release for all the seismic events was an order of magnitude smaller. Slow earthquakes (fault slip episodes without seismic radiation) are usually defined as one of three main types: 1) $S_p$ - Slow earthquakes that precede, and evolve, into larger "normal" earthquakes, 2) $S_f$ - Slow earthquakes that are triggered by "normal" earthquakes, and 3) $S_{MS}$ - Slow earthquakes with no associated seismicity. This event indicates a fourth type, $S_{MS}$ - Slow earthquakes with minor associated seismicity. In any case, this event was the first of this size and depth observed during 10 years of monitoring along the San Andreas fault that produced unambiguous strain on three independent instruments, clear associated seismicity and subsequent surface creep.

[3] NUCLEATION SIZE OF MODERATE EARTHQUAKES AND KINEMATICS OF THE SAN ANDREAS FAULT IN CALIFORNIA FROM SUBMICRO HZ TO 30 HZ STRAIN MEASUREMENTS

Popular views of the earthquake rupture process and fault kinematics include suggestions of: 1) non-linear deformation prior to rupture in regional-scale "preparation zones" of earthquakes, 2) strain redistribution by "crustal block interaction", 3) propagating aseismic slip waves, and 4) variation in the material properties of near-fault materials with time and location. In contrast, submicro-Hz to 30 Hz high-resolution strain through many moderate earthquakes in California and Japan indicate: 1) short-term non-linear precursive strains greater than nanostrain rarely occur in the eventual epicentral region prior to rupture, 2) fault patches that initiate large scale failure are apparently less than a few hundred meters in size, 3) strain redistribution from earthquakes is transmitted largely elastically through the complex geology and fault geometry in these regions, 4) aseismic slip at depth is apparently largely uniform at seismogenic depths but episodic in the near-surface material, and 5) material properties are invariant on timescales of days to years. Only one clear example of a deep slip episode (slow earthquake?) has been detected. These results are supported by near-field continuous strain data during more than 50 recent events on the San Andreas and associated faults with magnitudes ranging from 7.3 to 4.5 and continuous strain during numerous surface fault slip episodes. Similar events in Japan have similar characteristics. The apparent small size of the rupture initiation moments compared to the total earthquake moments suggests that there is no scaling of the nucleation process with earthquake magnitude. The basic failure process thus apparently involves rupture nucleation and runaway. High pore pressure fluids may be associated with this process but pore pressure redistribution must also be limited in extent. Detection of rupture nucleation apparently will require these highly sensitive and stable instruments be installed even closer to the hypocenters of large earthquakes than we have been able to accomplish during the past 10 years.


Two continuously operating proton magnetometers, LSBM and OCHM, at distances of 17.3 km and 24.2 km, respectively, from the epicenter of the June 28, 1992, $M_W$ 7.3 Landers earthquake, recorded data through the earthquake and its aftershocks. Seismomagnetic offsets of -1.2±0.6 nT and -0.7±0.7 nT were observed at these sites. In comparison, offsets of -0.3±0.2 nT and -1.3±0.2 nT were observed during the July 8, 1986 M_L 5.9 North Palm Springs earthquake which occurred directly beneath the OCHM magnetometer site. The observations are generally consistent with seismomagnetic models of the earthquake in which fault geometry and slip have the same form as
that determined by either inversion of the seismic data or inversion of geodetically
determined ground displacements produced by the earthquake. There is no indication
of diffusion-like character to the magnetic field offsets that might indicate these effects
result from fluid flow phenomena. There are no indications of enhanced low-
frequency magnetic noise before the earthquake at frequencies below 0.001 Hz.

[5] CONTINUOUS BOREHOLE STRAIN IN THE SAN ANDREAS FAULT
ZONE BEFORE, DURING AND AFTER THE JUNE 28, 1992, Mw 7.3
LANDERS, CALIFORNIA, EARTHQUAKE.

High precision strain was observed with a borehole dilational strainmeter in the
Devil’s Punchbowl during the 11:58 UT June 28, 1992, Mw 7.3 Landers earthquake
and the large Big Bear aftershock (Mw, 6.3) that occurred about three hours later. The
strain during the earthquake at this instrument shows no apparent amplification effects
that might result from compliant faults. There are no indications of precursive strain
due to either local slip on the San Andreas or precursive slip on the eventual Landers
rupture. The observations are generally consistent with models of the earthquake in
which fault geometry and slip have the same form as that determined by either inver­sion
of the seismic data or inversion of geodetically determined ground displacements
produced by the earthquake. There are some indications of minor postseismic behavior
during the several months following the earthquake.

[6] ELECTROKINETIC EFFECTS ASSOCIATED WITH CHANGES IN HIGH
PORE PRESSURE COMPARTMENTS IN FAULT ZONES - APPLICA­
TION TO THE LOMA PRIETA ULF EMISSIONS

We determined the electric and magnetic fields generated during failure of faults
containing sealed compartments with pore pressures ranging from hydrostatic to lithos­
tatic levels. Exhumed fault studies and strain measurement data limit the possible size
of these compartments to less than 1 km in extent. Rupture of seals between compart­
ments produces rapid pore pressure changes and fluid flow and may create fractures
that propagate away from the high pressure compartment, along the fault face. Non-
uniform fluid flow results from pressure decrease in the fracture from crack generated
dilatancy, partial blockage by silicate deposition, and clearing as pressure increases.
The direct consequences of this turbulent fluid flow are associated transient magnetic
signals caused by electrokinetic, piezomagnetic, and magnetohydrodynamic effects.
Models of these processes for fault geometries with 1 km high pressure compartments
show that electrokinetic effects are several orders of magnitude larger than the other
mechanisms. The electrokinetic signals produced by this turbulent flow are compar­
able in magnitude and frequency to the magnetic signals observed prior to the ML 7.1
Loma Prieta earthquake of 18 October 1989 provided fracture lengths are less than 200
m.

[7] DIFFERENTIAL MAGNETOMETER ARRAY IN CALIFORNIA

We continue investigations of local magnetic fields and relationships to crustal
strain and seismicity in the Parkfield region and in southern California. The network
consists of 9 stations which are all sampled synchronously every 10 minutes and
transmitted with 16-bit digital telemetry to Menlo Park, CA through the GOES satel­
ellite. Data are monitored daily with particular attention to the seven stations operating
in the Parkfield region of central California and the three stations operating in the
Long Valley caldera. At these latter sites a magnetic field anomaly first became obvi­
sous in late 1989 and in continuing to the present in concert with anomalous 2-color
gedetic strain measurements and spasmodic swarms of minor earthquakes.

[8] USING SATELLITE TELEMETRY FOR NEAR REAL-TIME MONIT­
ORING OF SEISMIC EVENTS AND STATUS OF PORTABLE DIGITAL
RECORDERS.
Near real-time monitoring of seismic events and status of portable 16-bit digital recorders has been established for arrays near Parkfield, Mammoth Lakes and San Francisco, California. This monitoring system provides seismic event identification (rough location and magnitude) and a cost effective means to maintain arrays at near 100% operational level. Principal objectives in the design of this telemetry system have been portability and low cost. The system has been developed to utilize portable digital seismic recorders (GEOS-General Earthquake Observation System) and portable data collection platforms (DCP) for the Geostationary Operational Environmental Satellite (GOES) telemetry system. Data are transferred asynchronously from the GEOS seismic system through a microprocessor controlled interface every 10 minutes. The interface stores, determines priority, converts, and synchronously transfers these data to a Sutron Corp. Model 8004 DCP for transmission through the GOES satellite telemetry system. Event parameters include trigger time, peak amplitude, time of peak amplitude and event duration. Instrument configuration parameters, transmitted at system start up time and every 24 hours, include recording parameters, trigger parameters, GEOS software version, clock reference and location parameter. Instrument status includes battery voltage, number of events and percentage of tape usage. These data are transmitted as appropriate to the U.S. Geological Survey satellite downlink and computers located in Menlo Park, California where they are processed and displayed.


Continuous records from a borehole strainmeter and other instruments in the Long Valley caldera provide critical insights into the origin of at least one episode of minor seismicity in volcanic regions triggered by the June 28, 1992, M_L 7.5 Landers, California, earthquake. The strain transient reached a peak of 0.25 microstrain in the few days following the Landers event and decayed over the next 20 days. This corresponds approximately in time to the primary seismic moment release across a broad region of the south part of the caldera at a depth of between 4 to 5 km. Strain transients in 5-km geodetic lines across the south caldera are not apparent above the measurement resolution (4σ) of about 1 ppm in daily sampled data during the week following the earthquake. Initial modeling results indicate that a single pressure source at the location of that currently producing the 1989-present strain episode, or at other locations, cannot easily explain the strain and tilt transients without violating the 2-color geodetic data. A more likely scenario appears to be that of distributed pressure sources, such as expected from gas release during severe shaking, as the large amplitude surface waves passed through the region. This mechanism of advective gas overpressure in volcanic systems has been proposed by Sahagian and Proussevich (1992) and others earlier. We observed a peak stress from these surface waves of about 3 bars at a depth of about 200 m.

Reports


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CALIFORNIA BOREHOLE STRAIN NETWORK

Figure 1.
Figure 3. Strain and seismicity records during a slow earthquake north of San Juan Bautista from December 11 to December 20, 1992.
Figure 2. Strain and creep records during a slow earthquake north of San Juan Bautista from December 11 to December 20, 1992.
Data

The investigation of the crustal structure and complex fault geometries of the Bay Area is the main focus of the BASIX (Bay Area Seismic Imaging Experiment) research program. BASIX has been a multi-institutional endeavor conducted cooperatively with the USGS, UC Berkeley, Stanford and Pennsylvania State Universities, as well as Lawrence Berkeley Laboratory. Resources were supplemented by CALTRANS, NSF (CALCRUST-North) and DOE. The BASIX profiling cruise conducted in September 1991 provided coverage across the Coast Ranges from the Sacramento River delta into the San Francisco Bay and through the Golden Gate (Figure 1). Data were collected by deploying daily a complex survey geometry of up to 100 buoyed receivers in the Bay and delta waters, and two non-coincident 15 km-long passes of the airgun ship through the line. Three land receiver arrays were also deployed to complement the marine data. In addition, under the related NSF CALCRUST-North program, approximately 172 miles of high-quality industry reflection data in the area have been acquired for study of the East Bay region. These results, coupled with numerous available well logs, have supplemented the BASIX effort.

Processing

Marine data. We have completed processing of the marine data from the north-eastern section of the profile, from the Sacramento River Delta into San Pablo Bay. Processing included trace editing, sorting to CDP gathers and velocity analysis. The final stacked section (Section A-A', Figures 1 and 2) combines three successive night's data (lines 101, 102, and 103) where they overlap to obtain the maximum possible CDP fold. The resulting data quality is quite good in the Delta and Suisun Bay waters at the east end of the survey.

Land data. A land receiver array of twelve channels of 8 Hz geophones was deployed with two RefTek 72A-02 recorders consecutively at three sites - on the Concord Naval Weapons Station on Suisun Bay ("B" in Figure1); at Point Pinole, in two 6-channel arrays straddling the Hayward fault ("C"); and at the east abutment of the Bay Bridge ("D"). The arrays were operated for several days in each deployment while the ship was shooting in the vicinity of that site.

The data were initially sorted to common receiver gathers for editing, filtering, and plotting with increasing source-receiver offset. Offsets range from 2-3 km to 18 km. Spiking deconvolution and filtering eliminated a "ringing" noise in the data, and considerably improved its quality. We have presently examined recordings from line 103 (the eastern-most shooting) to line 110, in San Pablo Bay. The resulting receiver gathers for lines 108-110 in San Pablo Bay, with the array at Point Pinole, exhibit apparent deep reflections (Figure 3). The marine receiver gathers in the same area did not show these arrivals clearly.

Further processing involved CDP sorting and the generation of initial stacked sections. The maximum CDP fold is very low compared to the marine recordings. Figure 4 is a preliminary stack from line 103 in Suisun Bay: Even though refractions obscure the very long offsets, the evident reflections compliment the interpretation of the deep reflectors on the equivalent marine profile.

Geologic Interpretation

The area of focus for geologic interpretation is shown Figure 5, including the BASIX ship's track with kilometer markings, the industry reflection lines obtained under the CALCRUST project, and exploration wells. Last year we examined the geology of the Sacramento Delta area in terms of terranes and the possibilities of large, relatively mobile, crustal blocks. We now have interpreted a complexly inter-leaved set of thin and thick wedges vertically stacked over a seismically active structure in the basement (Figure 6). The important elements in the neotectonics are structural blocks which may or may not coincide with ancient terrane boundaries. These blocks are bounded by active faults which can be roof faults or sole thrusts of tectonic wedges, or strike-slip faults. Based on the (1) distribution of seismicity near Pittsburgh on Suisun Bay (Figure 6a), (2) the velocity models of Tom Brocher (also from BASIX data, Figure 6b), (3) stratigraphic correlation of outcrops and well logs with reflection data (Figure 6c), and (4) location of the magnetic basement from gravity and magnetic models of Griscom and Jachens (USGS,
personal communication), we see evidence for a shallow tectonic wedge under Suisun Bay, a deeper wedge of Great Valley Sequence, and an even deeper wedge of Franciscan material over magnetic basement at about 14 km depth. The pattern of deep seismicity under the town of Pittsburgh (e.g., the M 3.0 temblor of December 5, 1993 at 17.5 km depth) is indicative of deformation within the basement, though the style of deformation is as yet unclear (Figure 6a). The magnetic signature of the basement suggests it is composed of ophiolite, but outcrop evidence along the San Andreas Fault favors a metamorphic lithology. While the gross pattern of deep seismicity beneath Pittsburg gives the appearance of a single, steeply dipping continuous fault, the detailed distribution of hypocenters suggests a stacked set of wedge-related faults. Further analysis of the fault mechanisms of these deep earthquakes is in progress.

Comparisons with other tectonic wedges at Dunnigan Hills to the north and at Kettleman Hills to the south reveal the uppermost wedge in the Sacramento Delta is thinner and shallower. The wedge may originally have been thicker and was since uplifted from below by the insertion of a newer, deeper, wedge, perhaps along the basement interface. Evidence for reactivation, and in some cases reversal, of faults suggests several episodes of tectonism in this region since the Late Cretaceous. We plan remapping and dip analysis of outcrops in the Vaca Mountains and the Los Medanos Hills, following the method of Lucchitta and Suneson (1993), to illuminate the tectonic history.

Identified Faults

The fault zone identified at kilometer 15 on the BASIX line is the southern extension of the Kirby Hills fault. Its location is also recorded on high-resolution uniboom data (also from BASIX) as well as on a proprietary Chevron line running parallel to BASIX, south of the river (Figures 1 and 5). Because the Kirby Hills fault does not appear to connect with the mapped fault at Antioch, we proposed to rename it the Pittsburg/Kirby Hills fault (PKHF) to distinguish it. The PKHF is seen on the CALCRUST lines 3 and 11 miles north of the river. North of Kirby Hills and south of the river, the fault changes from a steeply dipping set of faults that have a flower-structure appearance to a simple west-verging thrust that dips 30 degrees east. The deep seismicity in this area does not appear to be associated with this shallow fault (because of the interpreted intervening structures). And while the PKHF passes very near a major power plant and much recent urban development at Pittsburg, it is perhaps not displacement from this shallow fault that creates a seismic hazard here so much as more wide-spread ground-shaking due to potential larger (>M5 or 6) earthquakes in the deeper zone of seismicity (>14 km).

Another thrust fault is recognized at kilometer 25 on the BASIX line (Figure 5). This fault lines up with the mapped fault at Ryer Island and is also seen on the Chevron line south of the river. We propose to name this fault the Ryer Island fault. This fault lies subparallel to, and north of, the Los Medanos thrust (LMT), the major structure that underlies the Los Medanos Hills. South of the LMT the Montezuma Formation, a Pleistocene river gravel deposit, is involved in severe folding, and is overturned along the LMT. While some of the thrusting and shortening along the LMT zone may be older than Pleistocene, there has clearly been a great deal of post-Pleistocene action. How these structures fit together is the subject of continued investigation.

References:

Presentations at the 1992 Fall AGU meeting:

Presentations at the 1993 Fall AGU meeting:
Band, J.W., D.L. Jones, and T.V. McEvilly, Tectonic wedges and blocks at the eastern margin of the Coast Ranges, Sacramento Delta Area, California, EOS, 74, 609, 1993 (abs.).

Papers in Press:
Figure 1. San Francisco Bay region with BASIX profile line. Line A-A' indicates subsurface coverage of lines 101-103 (Figure 2). Letters B, C, and D show the location of UCB land recording arrays.
Figure 2. Final CDP stack of the eastern portion of the BASIX line in Suisun Bay (lines 101 to 103), referenced to Figure 1 (A-A'), with interpretation.
Figure 3. Receiver gather from the Point Pinole southern land array ("C" in Figure 1) for line 110. The vertical axis is two-way travel time. The apparent mirror-imaging of the section is due to the air-gun ship making two passes of the line, first north-to-south, then south-to-north. Note the band of discontinuous reflections at 9-11 sec, also apparent on the land recordings for lines 108 and 109.
Figure 4. Preliminary CDP stack from the land recording at the Concord Naval Weapons Station ("B" in Figure 1).
Figure 5: Map of Sacramento Delta area showing location of the BASIX line with kilometer markings, important geomorphic features, newly mapped faults, and subsidiary data sets.
Figure 6: East-west cross sections (no vertical exaggeration) coinciding with the BASIX line, and extending from the Central Valley on the east to the Hayward Fault on the west. a) Seismicity in the vicinity of Pittsburgh on Suisun Bay, with the depth of onset of ductile flow (Chi Wang, personal communication), and the velocity model of Brocher, 1993, based on BASIX refraction data (personal communication), shown as contours in km/sec. b) geologic cross-section based on BASIX seismic profile, outcrop and well data, and depth to magnetic basement from Jachens (1993, pers. comm).
Annual Technical Report
USGS 1408001-G2136  Program Element II.2
Tectonics of the Mission - Chabot Faults
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Summary

This study focused on the seismically active area east of Fremont (Figure 1) that is unrelated to previously known active faults, as well as adjoining areas from Garin Regional Park in southern Hayward to an area southeast of San Jose (Plate 1). Significant new discoveries resulting from the study in fiscal year 1993 include:

1) Active seismicity is located in a band of previously unmapped transpressional faults, including the Sheridan Creek and Dresser Faults, as well as the previously mapped (Hall, 1958) segment of the Mission Fault on and northwest of Mission Peak.

2) Faults previously mapped (Crittenden, 1951, Hall, 1958, Dibblee, 1980) as unrelated fault segments (i.e. Warm Springs, Mission, Arroyo Aguague Faults) are actually part of a continuous belt of faults that runs subparallel to and between the Calaveras and Hayward Faults (Plate 1).

3) At least three phases of deformation are seen in the belt; an early transpressive stage (probably pre - Pleistocene), an attenuation stage (Pleistocene or younger), and a late transpressive stage (Pleistocene or younger, probably related to active seismicity, see above).

4) The Mission and Chabot Faults, previously mapped (Hall, 1958, Dibblee, 1980) as continuous and equivalent are actually distinct. The transpressive Mission Fault cuts the older, attenuation, Chabot Fault.

5) A large component of fault normal deformation (at least 100%) has occurred across the fault belt, as evidenced in the southern portion by the repetition of lenses of ophiolite rocks on faults there (Figure 2 A-D). Because the belt is subparallel to the Hayward and Calaveras Faults, it is unlikely that compression is due to bending or asperities on strike - slip faults. Rather, compression is probably related to movement of upper crustal blocks and strike - slip faults bounded below by a mid - crustal decollement.

Introduction

The initial impetus for this study was the observation that a large number of small earthquakes defined a zone of active seismicity that is unrelated to the major faults, the Hayward and Calaveras Faults, in the area southeast of the town of Hayward (Fig. 1). The seismically active zone was in the general area of a reverse fault named the Mission Fault, best mapped on
This fault was mapped by Hall (1958) as the southward extension of the Chabot Fault, which runs subparallel to the Hayward Fault from Oakland south through Hayward. However, the Chabot Fault offsets strata in a way consistent with normal faulting, not reverse faulting as suggested for the Mission Fault. We initially proposed to study the Mission-Chabot Fault zone to understand its relationship to the seismically active zone and to the Hayward and Calaveras Faults, as well as to understand the nature of fault motion, bedrock relationships, amount of offset, and potential seismic hazard. By the end of fiscal year 1992 this study had shown that the previously mapped location of the Mission Fault on Mission Peak was in error, and the fault and the surrounding strata were remapped. The Mission Fault is indeed a reverse or transpressional fault, with approximately 500 meters of uplift on the east (hanging wall) side. The study also showed that the Mission Fault was only one of a large number of faults in the area, and field work had begun in order to study the regional tectonic framework and to understand the role of the Mission Fault and the seismically active zone. In particular, work in the Silver Creek area of southeast San Jose, site of recent construction excavation, had revealed a major thrust or transpressional fault that had placed Franciscan rocks and Coast Range Ophiolite on top of Pliocene conglomerate. Field work in the area showed that the thrust relationship was widespread, and that the amount of compressional deformation represented by that structure was on the order of ten kilometers.

In fiscal year 1993 we have proceeded with the study in three distinct but related ways:

1) Detailed study of the Mission and Chabot Faults
2) Regional study of faults related to the seismically active zone
3) Regional study of the tectonic framework.

These three aspects are described below.

Detailed Study of the Mission and Chabot Faults

This study showed that the Mission Fault is a continuous strand that trends north-northeast for about 50 kilometers. To the north of the type locality at Mission Peak, the fault forms the range front fault for a series of hills. The fault itself is covered by Holocene alluvium, and no evidence was found for Holocene movement on any segment of the fault. However, trenching or other very small scale studies were not undertaken by this group, so the age of last fault motion is not precisely known (trenching studies of the Mission Fault are being undertaken by geologists at Lettis and Associates and at Woodward Clyde). North of Niles Junction the Mission Fault splays into two subparallel strands. The eastern strand offsets Pleistocene gravels (age estimate provided by E. Helley, U.S. Geol. Survey, oral communication, 1992) north of the abandoned railroad grading at the Old Vallejo Mill Site at Niles Junction. Continuing north, the two splays run almost parallel to the Hayward Fault until they merge into a very complex set of faults that are found on the east side of the Hayward Fault in Garin Regional Park in south Hayward (see Plate 1). South of Mission Peak, this study showed that the main strand of the Mission Fault is a reverse or transpressional fault that marks the contact between the overlying (hanging wall) Miocene Briones Formation and the underlying (footwall) Pliocene Orinda Formation (see Graymer and others, 1993, for rock unit descriptions). Although this contact was originally mapped (Crittenden, 1951, and Dibblee, 1973) as depositional and overturned, field studies showed that the beds are not overturned, so the contact must be considered a fault. In addition, as on Mission Peak itself, the contact truncates structural and depositional trends,
further supporting the idea of a fault contact. Furthermore, the contact between the Briones and Orinda Formations along trend to the south was mapped by Dibblee (1973) as a fault in the area east of Alum Rock Park. He named the fault there the Arroyo Aguague Fault, but it is actually the southern extension of the Mission Fault. The Mission - Arroyo Aguague Fault runs some 30 kilometers southeast of Mission Peak, subparallel to the Calaveras Fault along most of the length until it joins the Calaveras Fault in San Felipe Valley (see Plate 1). The Mission Fault is therefore a 50 kilometer long transpressional fault with documented Quaternary offset that joins the Calaveras Fault in the southeast and the Hayward Fault in the northwest. It should be noted that the Mission Fault is subparallel to the major faults along much of its length, but deformation on it has a consistent reverse component, so the reverse motion is probably not related to bends or asperities in the major strike - slip faults (as suggested by Andrews and others, 1993). This transpressional motion will be discussed more below.

The Chabot Fault was traced from Garin Park south to Niles Junction. At Niles Junction it cuts Pleistocene gravels (age estimate provided by E. Helley, U.S. Geol. Survey, oral communication, 1992), but is itself cut by the Mission Fault. It is an east dipping fault that is along most of its length the contact between the Jurassic and Cretaceous Knoxville formation on the west (the footwall) and Cretaceous sandstone and shale on the east (the hanging wall). The normal component of offset on the Chabot Fault suggests that it should not be considered a part of the Mission Fault system, but that it is probably the result of a Pleistocene or younger period of attenuation deformation that predates the transpressional deformation on the Mission Fault.

Regional study of faults related to the seismically active zone

The Mission and Chabot Faults are not the only faults in the seismically active zone. This study found a broad zone of faults running roughly parallel to the Mission Fault. These can be divided into three groups: younger reverse or transpressional faults, normal or attenuation faults, and older transpressional faults. Several transpressive faults have observable Pleistocene or younger displacement, including the northern segment (north of the Warm Springs Fault) of the Mission Peak Fault, the Warm Springs Fault, and the Sheridan Creek Fault, and many others, including the Dresser Fault and the southern segment of the Mission Peak Fault, have no documented Quaternary offset, but cut older faults and appear to belong in this category. Transpressive faults have placed older strata structurally on top of younger, but are distinguished from simple thrust faults by having an unknown (but possibly large) amount of strike - slip offset. Younger transpressive faults in the Niles Quadrangle all dip to the northeast. Some attenuation faults in the seismically active zone, including the Chabot Fault and the Palomares Fault, cut Pleistocene strata but are themselves cut by younger transpressive faults, while others, including the Pirate Creek Fault, have no observed Quaternary offset but probably belong to this group. Attenuation faults place younger strata on older strata that was previously separated by intervening rocks that have been tectonically removed, but differ from simple normal faults in that they have unknown, but possibly large, amounts of strike - slip offset. Finally, the oldest faults are the unnamed faults that have transpressive motion but are cut by attenuation faults. The older faults dip both northeast and southwest. This complex history of faulting has left a "braided" pattern of faults, which is most pronounced in a band about 2 kilometers wide running from the Niles Junction area through the area including and east of Mission Peak. This is the seismically active zone, but the precision of location of epicenters is not sufficient to allow pinpointing which
II

are the active strands at this time. However, structural arguments presented above would suggest that younger transpressive faults, such as the Sheridan Creek, Dresser, and Mission Peak Faults, are the strands displaying active seismicity. These faults are documented in the new geologic map of the Niles 7.5 minute quadrangle prepared by us (Graymer and others, 1993, in press).

Regional study of the tectonic framework.

The seismically active zone represents just the northernmost portion of a broad belt of north by northwest trending, mostly transpressional faults that extends at least as far south as Morgan Hill and includes the southern part of the Hayward Fault (Plate 1). Structural repetition of the Coast Range ophiolite in the southern portion of the belt defines at least four structural blocks that are separated by east-dipping imbricate faults of Quaternary age in the East Bay Hills, west of the Calaveras fault (Figure 2 A-D). Transpressive displacements along these faults, which include the Silver Creek, Quimby, Crosley, and Clayton strands, emplace rocks as old as Middle Jurassic onto Plio-Pleistocene non-marine deposits, including the Santa Clara, Packwood, and Irvington Gravels. Several of these faults exhibit evidence for Holocene displacements, including active seismicity, fault scarps, and offset stream drainages. Because strikeslip displacements of uncertain magnitude probably predominate on these and related faults throughout the region, it is not yet possible to make palynspastic reconstructions or to construct balanced cross sections. Nevertheless, the amount of shortening represented by structural repetition alone is on the order of at least 100%, or 10 km. This represents a possible local compressional component of plate motion of 10 mm/yr. for the past 1 my. This estimate should be considered a minimum, because it does not take into consideration structural complexities, such as folds and minor faults, within the blocks defined by repetition of ophiolitic rocks.

The presence of thrust faults in this region has been previously attributed to bending along a change in structural trend from N30°W on the Calaveras fault to N38°W on the Hayward fault (Andrews and others, 1993). This study shows, however, that some of the compressive faults are parallel to the Calaveras fault, and others extend far beyond the region of the bend, suggesting that differential movements along transpressive structures are themselves responsible for the change in structural trend. We have submitted these results as an abstract for the A.G.U. December 1993 meetings (Jones and Graymer, 1993, in press).

The compressional component of faults in the region requires that the major strike slip faults of the area, including the San Andreas and Calaveras Faults, have moved closer together in the past few million years. The implication of the large amount of Neogene shortening and the resulting relative motion of strikeslip faults is that faults of the San Andreas fault system must root in a decollement, and that the blocks intervening between major fault strands must be bounded below by a horizontal detachment surface on which the blocks as well as their structural boundaries can move laterally. This is discussed more completely in Jones and others (1993, in press).

An important result of the horizontal motion of structural blocks is differential uplift of various blocks throughout the region. Although the exact uplift rates for most faults in the region has not been calculated, this study has allowed local estimates of Neogene uplift to be made for the Mission Fault and for the Hayward Fault in the Fremont area. Based on offset of depositional contacts of late Miocene or early Pliocene rocks, a minimum of 1700 feet of vertical displacement is required on the Mission Fault (Graymer and others, 1993, in press). Comparison of the
elevation of depositional contacts of early Quaternary gravels on bedrock on either side of the Hayward Fault demonstrates at least 1000 feet of Quaternary vertical offset on that structure (Figuers, written comm., 1992). It is important to note that this vertical offset on the Hayward Fault occurs on a fault generally considered to exhibit only strike-slip motion, and in addition, it occurs at a position where the fault is relatively straight, and so is not the product of uplift at fault bends.

Conclusions

The Mission Fault is an east dipping, reverse or transpressional fault, that has Pleistocene or younger offset. It joins the Calaveras Fault at its southeastern end, and the Hayward fault at its northwestern end. It is also mapped as the Arroyo Aguague Fault by Dibblee (1973) along its southern portion. It is probably not part of the same fault system as the Chabot Fault, which is an east dipping attenuation or normal fault that also cuts Pleistocene alluvium. The Mission Fault cuts the older Chabot Fault in the area of Niles Junction. The Mission Fault is one of a number of east dipping transpressional faults that are probably the locus of the zone of active seismicity in the area. The seismically active zone is, in turn, the northeasternmost part of a transpressional system of faults that has resulted in compressional deformation of at least 100% in the region. The implication of this compressional deformation is that the major strike-slip faults have moved closer together in the Neogene, and so must root into a mid-crustal decollement. The implication of Quaternary offset and historic seismicity in the transpressional fault system is that these faults should be considered active. However, more detailed study of these faults is required to estimate such factors as recurrence interval and maximum credible magnitude.

Products of the Study

We have, as noted above, several publications in press related to our work on this project. We have submitted a new geologic map of the Niles 7.5 minute quadrangle, along with cross sections and other supporting material, to the U.S. Geol. Survey in Menlo Park for publication as an Open-File Report (Graymer and others, 1993, in press). Our manuscript, "Neogene Transpressive Evolution of the California Coast Ranges," has been accepted by Tectonics for publication (Jones and others, 1993, in press). Russell Graymer was co-leader of the Peninsula Geological Society Field Trip in November that discussed the geology and tectonics in the area of this project (Graymer and DeVito, 1993). And Russell Graymer presented a talk, "Structural Significance of Quaternary Imbricate Thrust Faults in the East Bay Hills South of Hayward, Central California Coast Ranges," at the December 1993 American Geophysical Union meeting (Jones and Graymer, 1993, in press). In addition, we have been participating with researchers at the U.S. Geol. Survey, Menlo Park, including E. Brabb and C. Wentworth, in preparing new geologic maps of Contra Costa, Alameda, and Santa Clara Counties. The new understanding of fault distribution and relationships, as well as rock distribution, from this project will be integrated into those new maps.
References


Figure 1 Map of East Bay region showing distribution of earthquake epicenters and major faults. Epicenter data from USGS 1980-1986 catalogue. Note that epicenter locations diverge from the Calaveras Faults south of Fremont and trend northwesterly near the Mission Fault before merging with the Hayward Fault north of Hayward.
Plate 1A
Fault Map of the
Southeast Bay Area
Hills (North Part)
Plate 1B
Fault Map of the
Southeast Bay Area
Hills (South Port)
Figure 2A–C
Cross sections showing intricate transpressive faults on the west side of the Diablo Range in the southeast Bay Area. Geologic units as follows:
JKI - Franciscan rocks
Jo - Coast Range ophiolite
MzCz - Upper Mesozoic and Cenozoic marine strata
uCz - Miocene to Pliocene non-marine strata and volcanic rocks
Pliocene and Pleistocene non-marine gravels;
QTs - Silver Creek gravels
QTP - Packwood gravels
QTi - Irvington gravels.
Figure 2D
Generalized geologic map showing imbricate transpressive faults on the west side of the Diablo Range in the southeast Bay Area Hills. Geologic units as in Figure 2A-C.
Proposal to Collaborate with the USGS Deep Continental Studies Group on the Northern Deployment of the Pacific Northwest Refraction Experiment

Agreement No. 14-08-0001-G2073
Program Element II.1

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INVESTIGATIONS UNDERTAKEN

In September of 1991, the University of Texas at El Paso (UTEP) participated in a cooperative seismic refraction experiment consisting of a series of profiles in western Washington and Oregon. This effort involved the United States Geological Survey, Oregon State University, and Canadian groups headed by the University of British Columbia. The UTEP group has concentrated on analyzing the results of the western Washington profile (Figure 1). Our investigations have consisted of an analysis of the seismic data employing a combination of forward and inverse modeling integrated with other data such as earthquake locations, drill hole information, geologic mapping, aeromagnetic surveys, and gravity readings.

RESULTS

As part a UTEP PhD dissertation (Gridley, 1993), a velocity model has been derived from seismic data acquired during the 1991 seismic experiment in western Washington. Intriguing results from the model include evidence for an extremely heterogeneous upper crust that contains deep, segmented basins as well as a -5 km thick high velocity layer interpreted as an ophiolite, and an arched crust–mantle interface that mimics structure within the subducting Juan de Fuca plate. The Moho geometry found in the velocity model has led to significant revisions in our view of crustal thickness variations in the region.

During the 1991 seismic experiment in western Washington, ten dynamite shots were detonated at approximately 30 km intervals along a north–south transect that began at the Canadian–U.S. border near Mount Baker and extended through the Puget Basin to the Cowlitz River, south of Mount Rainier (Figure 1). The shots were recorded by over 500 instruments deployed at approximately 600 m intervals along the 300 km–long transect. Key phases observed in the data (Figure 2) include Pg, PmP, a mid-crustal reflector (MCR), reflections from the top and base of the oceanic crust composing the upper portion of the subducting Juan de Fuca plate, and reflections from the top and base of a high velocity layer in the upper crust. These arrivals were modeled using a combination of seismic inversion (Zelt and Smith, 1992) and forward ray tracing (Luetgert, 1992).

The entire resulting velocity model is shown in Figure 3 and a close-up of the upper crustal structure is shown in Figure 4. To say the least, this model is much more complex that the primarily 1-D models to which previous studies were limited. Our model reveals a heterogeneous upper crust, and a continental Moho that arches above a similar arch in the subducting Juan de Fuca plate. The upper
5 km of the model is dominated by the structure of the Puget Sound Basin. The basin is divided into a number of sub-basins bound by steeply dipping interfaces that presumably represent faults. Velocities within the basin range from 2.0 to 4.7 km/s. At depths between 4 and 8 km in the northern third of the transect a -3 km thick high velocity layer that is apparently floored by -3 km-thick low velocity layer occurs. We interpret the high velocity layer as an ophiolite. This is consistent with the wide-spread occurrence of middle to late Jurassic ophiolitic rocks in local outcrops. On average, the velocities obtained in the upper 10 km are substantially lower than the 5.4 to 6.6 km/s values now being used in earthquake locations (Crosson, 1976).

The most striking feature of the structure of the mid- to lower crust is the marked arch in the Moho that causes depth-to-Moho to range from 38 to 48 km across the transect. This geometry is constrained primarily by PmP arrivals. Velocities in the mid-crust vary from 6.4 to 6.85 km/s (Figure 3) and generally increase from north to south. These values are in general agreement with those found by Lees and Crosson (1990). In the lower crust, velocities range from 6.7 to 7.4 km/s (Figure 3). An early study by Crosson (1976) determined a range of 6.6 to 7.0 km/s for the lower crust. Wide-angle reflections from the top and base of the oceanic crust of the Juan de Fuca plate occur in seismic data from the northernmost and southernmost shots. Modeling of these events produces an arch in the Juan de Fuca plate consistent with that obtained from earthquake data and teleseismic waveform modeling (Crosson and Owens, 1987; Weaver and Baker, 1988).

The new north-south velocity model has led to significant revisions in our picture of variations in crustal thickness in the region. A contour map of crustal thickness constructed by Mooney and Weaver (1989) indicated a pronounced eastward thickening of the crust from 16 km at the continental margin to 40 km beneath the Cascade Range of western Washington. These results were based on limited refraction data and local seismic network data. Whereas this general trend remains in a revised crustal thickness map (Figure 5), the constraint of the new north–south model near 122° longitude and two additional gravity transects (Gridley, 1993), indicates that the crust–mantle boundary beneath the Puget Sound Region shallows and is locally arched in just the same location and manner that the subducting Juan de Fuca plate is (Figure 6). The 1-D velocity model currently being used by the University of Washington group for earthquake location assumes a crustal thickness of 41 km. Thus, an important implication of the revised crustal thickness map is that the crust may be 4 to 10 km thinner than assumed. Gravity modeling also indicates that continental crust east of Mt. Baker may exceed 50 km in thickness.

REFERENCES


REPORTS PUBLISHED


Index Map of the Pacific Northwest Seismic Experiment

Figure 1
Figure 2a Examples of MOHO Reflection (PmP)
Examples of Wide-Angle Rejections from the Low Velocity Layer at the Top of the Plate (LVL) and the High Velocity Layer Within the Plate (Plate)
Figure 3. Interpreted geological cross section from the seismic model. Numbers are velocity values in km/s.
**Figure 4**

**Detailed Velocity Structure in the Vicinity of the High Velocity Layer**
Figure 5. Contour map of crustal thickness for western Washington. Contour interval is 2 km. Dashed lines indicate extent of concentrated seismicity for the upper crust (20-30 km) and Juan de Fuca plate (40-50 km) determined from Weaver and Baker (1988).
Figure 6
Contour Map of the Depth to the Top of the Juan de Fuca Plate
(Modified from Crosson and Owens, 1987 and Weaver and Baker, 1988)
LATE HOLOCENE RELATIVE SEA LEVEL HISTORY AT CAPE BLANCO, OREGON

Annual technical report for award number: 1434-93-G-2321

Investigator: Harvey M. Kelsey

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Program Element II.5

Investigations Undertaken

The estuary and lowermost valley of the Sixes River, just north and inland of Cape Blanco in south coastal Oregon, was selected as a site to investigate late Holocene relative sea-level changes. This site straddles the axis of an anticline that deforms late Tertiary and Quaternary strata. Continued contraction of the anticline has tilted the Holocene valley fill to the south. Highway benchmarks near Cape Blanco have been displaced upwards at a rate of 4-5 mm/yr in the last 70 years (Mitchell et al., in press); therefore it appears that, interseismically, the Sixes River Valley is being uplifted relative to the geoid. Through our stratigraphic investigations, we will assess whether coseismic vertical displacements have occurred in the late Holocene, and whether they are up or down, or a combination of both.

The Sixes River site is well suited for the purposes of investigating late Holocene relative sea-level changes because an abandoned meander in the lower valley was inundated by rising eustatic sea level in the late Holocene, but is now emergent as a low-lying floodplain. We investigated the late Holocene stratigraphy at cutbanks along the lower Sixes River, in cores taken in the lower part of the meander valley and in cores taken in the upper part of the meander valley. Cores were taken using a 2.5-cm half-cylinder gouge core. Most cores were 3-5 m in length and core recovery was usually 100%. Field work took place in August and September, 1993.

Results

The following results are preliminary. Field work that was supported by this award has been completed but as of yet we have not received the results of organic samples submitted for AMS 14C age determinations. More field work is planned.

The sediment in the upper 5 m of the meander valley of the lower Sixes River is a dark-grey clay. Rapid changes in environment over the late Holocene are inferred from a sequence, repeated several times in many of the cores, of clay grading up into an organic-rich horizon, in turn abruptly terminated (contact < 0.5 mm) by a return up-section to clay. In some cases, a thin sheet of clean, medium-to-very-fine sand directly overlies the buried soil horizon. Eileen Hemphill-Haley of the U.S. Geological Survey has carried out a preliminary diatom analysis of selected samples from several cores in the upper and lower meander. The environment of deposition of the clay is primarily estuarine; but at deeper levels, a freshwater marsh environment is preserved in some places.
The cores taken in the lower meander show one to two buried soils in the upper 1.25 m of estuarine sediment. In all cores, a capping layer of sand is present above at least one of the two buried soils. The thickest sand layer is present in the core furthest inland from the river mouth; it contains three fining-upward packets of sand, which we interpret as three closely-spaced pulses of sand deposition. With the exception of one buried soil with a capping layer of sand in the lower portion of the core C, the deeper portions of the cores in the lower meander record massive clay of estuarine or freshwater origin, with some laminated units of very fine sand and clay. The laminated units of sand and clay may be of tidal origin.

There are five buried soils in the estuarine sequence in one of the cores in the upper meander site. The first and third buried soil from the top have capping layers of sand, and these sand layers, along with one sand layer in the furthest-inland core from the lower meander, are the thickest sands at any core site. The upper meander is 3.5 km up valley from the mouth of the Sixes River but only 400-700 m from the ocean through a 19-m low gap in the seas cliffs to the southwest. Assuming that these sands are deposited by tsunamis (a hypothesis that will be tested during further research), the sand thickness data can be interpreted in two ways. One explanation is that the tsunami traveled thousands of meters up from the mouth of the Sixes and only deposited sediment at the bay margin, which is now the upper meander site, because the lower meander site at that time was too deep. Alternatively, the tsunami traveled over the low gap in the sea cliff (present elevation 15-19 m above sea level) and thence deposited the sand in the upper meander site.

In addition to the cores, we logged in detail a 31 m-long, 4 m-high cutbank that is 3.4 river kms from the mouth of the Sixes River. We used an auger to extend the stratigraphic data down an additional 2 m. The site consists of alluvial gravels overlain by estuarine deposits overlain by fluvial overbank deposits. The site records two liquefaction events in the last 2,000 years; this age is based on a \(^{14}C\) age determination on detrital sticks within alluvium, which were collected several years ago during reconnaissance field work. In the first event, liquefied sands vented onto a paleovalley-floor surface, 1.5 m above the alluvial gravels, about 2,000 years ago. We have recognized several sand blows with feeder vents coming from source sands a few meters below what was the ground surface at that time. The one buried soil horizon exposed in the cutbank is a zone of \textit{in-situ} herbaceous roots associated with the same paleo surface onto which the liquefied sand vented. This paleo valley surface is now buried by 3 m of estuarine sediment and capped by 0.5 m of overbank sediment. The major environmental transition recorded at this site, from fluvial to estuarine conditions, thus occurs across the buried soil surface and across the horizon onto which liquefied sand was vented. The geologic features associated with the vented sand meet the criteria of Obermeier et al. (1985; 1990) for near-surface sand deposits liquefied and vented to the surface by seismic shaking.

A younger unit of liquefied sand is exposed in the same cutbank. This sand is associated with a second liquefaction event, which displays obvious cross-cutting relationships with the earlier one. During this event, liquefied sand was injected through veins and sills into fluvial sediments and overlying estuarine muds. The second event occurred after 3.5 m of estuarine clay and silt had been deposited above the layer of vented sand. Veins of sand penetrated to within 0.5 m of the present surface, though no evidence of venting has yet been found for the second event. The second event may be temporally related to the subduction zone earthquake of ca. 300 years ago (Atwater et al., 1991; Nelson and Atwater, 1993), and we are in the process of assessing this possibility. We have collected samples of the liquefied sands from both events for particle size analysis, and have collected woody debris that will allow us to better estimate the times of the two liquefaction events. We have been able to excavate down to the level of the source sand for both events.

We present two preliminary conclusions based on our work to date. First, in the past 2000 years, the lower valley of the Sixes River has experienced two episodes of shaking sufficiently severe to
liquefy fine-grained sand. The earlier liquefaction event vented sand onto a valley floor underlain by alluvium. The major environmental transition recorded at this site, from fluvial to estuarine conditions, occurs across a buried soil surface onto which liquefied sand was vented. On the basis of this stratigraphic data, we infer that the liquefaction event was accompanied by submergence of the valley. Second, the cores from the Sixes River valley show as many as five successive episodes where an organic-rich horizon was abruptly buried by estuarine or freshwater mud. For three of these burial episodes, an anomalous sand bed abruptly overlies the soils at some locations. One working hypothesis is that these buried soils represent times of sudden coastal subsidence (probably of <1 m) during a great earthquake and that the sand was deposited by tsunamis that arrived shortly after the subsidence.

Reports Published


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PALEOSEISMOLOGIC INVESTIGATIONS OF THE CENTRAL AND SOUTHERN REELFOOT SCARP, TENNESSEE

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TECHNICAL ABSTRACT

Investigations
The primary purpose of this research is to better constrain the timing and number of large earthquakes along the Reelfoot scarp in northwestern Tennessee. There are considerable uncertainties regarding the recurrence interval for large earthquakes along potentially seismogenic faults in the New Madrid Seismic Zone. Additional paleoseismic data are required to confidently evaluate the earthquake recurrence intervals, and hence seismic hazards, in the NMSZ.

This research will include detailed paleoseismologic investigations at one and perhaps two sites that show promise to provide constraint on the timing of surface deformation along the eastern side of the Reelfoot scarp. We intend to excavate a trench across a subtle topographic swale and air-photo lineament that is along the southern projection of the Reelfoot scarp and may be related to near-surface deformation. In addition, we have targeted two possible trench sites across the central part of the scarp. Because it is likely that scarp-derived colluvial deposits related to individual episodes of uplift are located at the base of the scarp (Kelson et al., 1992a, b; Simpson et al., 1992), we intend to excavate a trench across the scarp face at either of these scarp sites. We anticipate that these trenches will expose deformed and undeformed stratigraphy and provide data on the timing and number of episodes of surface deformation along the scarp. From this information we hope to assess the recurrence interval of large earthquakes associated with the scarp.

Results
The research was funded in mid-September, 1993. Over the past month, we have initiated the permitting process for excavations at a preferred site south of Reelfoot Lake, and at several other sites in the event that the preferred site is not feasible. Results will be forthcoming once permission to excavate is obtained.

Publications
(generated from previous project phase)


PALEOSEISMOLOGIC INVESTIGATION OF THE CALAVERAS FAULT AT LEYDEN CREEK, ALAMEDA COUNTY, CALIFORNIA

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TECHNICAL ABSTRACT

Investigations

The northern Calaveras fault, which traverses the western margin of the densely populated and rapidly developing San Ramon Valley, is a potential source of large earthquakes. Recent paleoseismic studies along the northern Calaveras fault at Leyden Creek (Kelson et al., 1992c, d) show that multiple surface-faulting events occurred during the late Holocene and that the fault slips at a rate of about 8 mm/yr. This paleoseismic research is designed to refine this slip rate estimate and to develop better age-estimates of the timing of late Holocene surface-faulting events. These data are required to constrain recurrence intervals for large earthquakes on the fault and to improve estimates of earthquake probability.

Results

Based on an offset buried valley margin, our previous studies show that the fault is moving at a rate of 8 ± 3 mm/yr (Kelson et al., 1992c, d). To better constrain the geometry and age of the buried channel margin, and thus the slip rate estimate, we completed an additional 10 auger borings (6-inch diameter) and 2 large-diameter (24-inch) borings, which provided exposures of fluvial strata to depths of about 12 m (40 ft). A total of 20 charcoal samples were extracted from cores or large-diameter borehole exposures to depths up to about 8 m (27 ft). Selected samples will be submitted for radiometric analysis; hopefully these will yield a well-constrained age-estimate of the offset valley margin and thus decrease the uncertainty in the slip rate.

Previous studies show that at least three and perhaps seven late Holocene surface-faulting events occurred at the site (Kelson et al., 1992c, d). To better constrain the timing of these events, we excavated three additional trenches, two across the fault and one parallel to the fault. These exposures reveal evidence of multiple rupture events and, in contrast to previous trenches at the site, abundant charcoal (43 samples so far). Documentation and interpretation of the trench exposures is in progress. Selected charcoal samples will be submitted for radiometric analysis; hopefully these will yield a well-constrained age-estimate of scarp-derived colluvial deposits and thus on the timing of paleoseismic events.

Publications

Publications (continued)


CASCADIA SUBDUCTION ZONE: NEOTECTONICS OF THE CONTINENTAL SHELF OFF OREGON AND WASHINGTON

CONTRACT 14-08-0001-G1800
CONTRACT 1434-93-G-2319
Program Element II.5

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Investigations

The overall objective of this study is to characterize and determine the timing of active faulting and folding in the subducting Juan de Fuca plate (abyssal plain), deformation front (accretionary wedge), and forearc basins (continental shelf) of the Cascadia convergence zone off Oregon and Washington. Within this framework, we are trying to determine if the prominent WNW-trending strike-slip faults and sigmoidally bent folds mapped on the continental slope can be traced across the continental shelf forearc basins in both shallow and deep crustal structures. We have investigated and characterized discrete oblique strike-slip fault and flexural-slip zones and are trying to relate them to potential fault and fold zones in the adjacent coastal region where co-seismic subsidence events in coastal bays are believed to be associated with large earthquakes in the Cascadia subduction zone. Marine field studies in 1993 were concentrated on known and potentially active deformation zones identified in the recently published neotectonic map of the Oregon margin and on the Washington margin map (in progress). In the first part of the year, we discovered six new WNW-trending active strike-slip fault zones on the abyssal plain and accretionary wedge off Oregon and Washington. In the second part of the year, we traced two of these faults zones onto the continental shelf off central and southern Oregon where they cut the Holocene sediments of the shelf. We have demonstrated conclusively that left-lateral strike-slip faults cut both the subducting Juan de Fuca plate and the overriding North American plate. These faults are imaged in sufficient detail that we have determined their distribution, orientation, geomorphology, sense of motion and, in at least two cases, their rate of slip and age.

Results

1. New Data Acquisition

We conducted a SeaMARC-IA high-resolution sidescan sonar cruise aboard the R/V Thompson from 23 April 1993 to 11 May 1993. While this cruise was sponsored by the National Science Foundation through a two-year grant to L. Kulm and R. Yeats, it addresses all of the deep-water (abyssal plain and continental slope) objectives of our NEHRP program. We collected approximately 2,000 km of sidescan records on both the Washington and Oregon margins at mainly 5-km swath widths with higher-resolution 2 km swaths being obtained in selected areas of the 5-km swaths. The sidescan data were collected on active strike-slip faults extending from the abyssal plain and continental slope to the outermost continental shelf of both margins (Fig. 1, faults 1-9). The sidescan targets were identified or inferred previously from seismic reflection records, and in all but one case, we confirmed the existence of a major fault. Digital Hydrosweep multibeam bathymetry data were also collected along the sidescan trackline, and swath contour maps were made.
Based upon our 1993 SeaMARC sidescan cruise, we were able to direct our September, 1993, NOAA Undersea Research Program (NURP) cruise to three areas on the Oregon outer continental shelf where an active strike-slip fault (Daisy Bank area and Coquille fault) and a flexural-slip fault (Coquille Bank area) were imaged and mapped by a high resolution AMS 150 kHz sidescan system (Fig. 1, DB, CF, CB). The submersible DELTA was used to map in detail and video tape selected portions of these active faults. These combined studies allow us to trace these faults from the abyssal plain to the continental shelf. The NURP program complements our NEHRP program by providing field data in the shallow waters of the continental shelf.

2. Active Strike-Slip Fault Zones of the Abyssal Plain and Accretionary Wedge

We have made significant progress in determining the distribution and physiography of the suspected fault zones and their sense of slip on both the Oregon and Washington margins. Using SeaMARC-IA sidescan sonar, we surveyed 10 suspected zones of oblique strike-slip faulting on the continental slope and abyssal plain from 43° N to 48° 10' N. Six new strike-slip faults were discovered, three in Washington (Fig. 1, faults 7, 8, and 9) and three in southern Oregon (Fig. 1, faults 1, 2, and 3), making a total of nine left-lateral faults. The six faults mapped in Oregon and three in Washington strike 298° to 283°, with obliquity to the margin increasing to the south. The three new faults are expressed prominently in swath bathymetry as irregular ridges composed of en echelon folds, and sigmoidal bends of throughgoing accretionary wedge folds. SeaMARC sidescan records of these structures reveal steep scarps cutting accretionary wedge folds and commonly show straight traces, reversals of vertical separation, and left-lateral horizontal offsets of submarine channels and other crossing structures. Furthermore, we obtained complete sidescan coverage along one known fault (Fig. 1, fault 5) and completed our coverage of another fault (Fig. 1, fault 6) previously studied in an NSF/ODP project (1989-1992). These newly mapped faults appear to be similar in most respects to the earlier mapped faults (Goldfinger et al., 1992), which cut both upper and lower plates, extending from the abyssal plain to the upper slope/outer shelf region.

While two of these fault zones (Fig. 1, faults 8 and 9) were previously discovered on the Juan de Fuca plate (Nitinat Fan) at the base of the continental slope in a water gun seismic reflection survey, their continuity, orientation, and slip direction were unknown. SeaMARC sidescan images now show that at least two of the faults cut the Holocene turbidite sediments of the fan which are overlain by 1.0 m of mud. The faults are oriented about 284°. The Holocene age of the faulted sediments is based on radiocarbon ages of the turbidites, the foraminiferan-radiolarian ratio, and a biostratigraphic indicator, dated at 13,000 years B.P in nearby piston cores. A late Pleistocene submarine channel on the fan is offset at least 150 m by the N. Nitinat fault in a left-lateral sense based on the sidescan record (Fig. 1, fault 9). If we assume that the last Pleistocene turbidite maximum was approximately 20,000 years ago (i.e., time of the highest rates of sand turbidite deposition during lowered sea level), we can calculate a slip rate of 7.5 mm/yr for this left-lateral strike-slip fault during this time. Retro-deforming the horizontal displacement of flat-lying reflectors in pre-existing seismic records in the vicinity of this fault (a technique described by Goldfinger et al., 1993), we calculate 2.5 km of left slip during the past 390,000 yrs ± 44,000 yrs (i.e., the initiation of fault movement in the section), producing a slip rate of 6.3 mm/yr ± 0.7 mm/yr. These rates are comparable to the 5-12 mm/yr and 7-10 mm/yr rates, respectively, of slip determined for fault 6 (the Wecoma fault, Fig. 1) off Oregon by Goldfinger et al., 1992. ODP drill site 888 (Leg 146) on Nitinat Fan provides the age control and rates of turbidite sedimentation for the fan while piston cores provide a high resolution control for the past 20,000 years in the vicinity of the fault. This same technique will be used for other faults. The sidescan images show that the faults continue up the continental slope where folds on the accretionary prism are displaced left-laterally, producing a sigmoidal map pattern. In at least one case, channels or canyons on the upper continental slope appear to be controlled by a strike-slip fault.
3. Active Strike-Slip and Flexural-Slip Faults of the Oregon Shelf

We mapped one of the major oblique strike slip faults (Fault B, i.e., fault 5 in Fig. 1) in considerable detail near Daisy Bank (DB) on the Oregon outer continental shelf. We discovered that Fault B cuts the seafloor in the youngest Holocene sediments, and we observed from DELTA fresh scarps disrupting unconsolidated olive grey Holocene sediments and exposing late Pleistocene grey cohesive clays along subsidiary scarps <1.0 m high. This distinctive color change in the sediments occurs at about 11,000 years B.P. based upon radiocarbon dating of upper slope deposits (Barnard and McManus, 1973). The main scarp was measured by submersible at several locations, and averaged 45 m. Fault B has several characteristics consistent with our previous inference that it is a left lateral strike-slip fault: (1) left-lateral drag folding of older bedding ridges adjacent to the fault (noted in the SeaMARC sidescan image); (2) reversal of vertical separation along strike, a common feature of strike-slip faults; and (3) consistently straight trace along the seafloor, indicating a near vertical fault. These morphological indicators support the earlier interpretation of left-lateral strike-slip faulting on this fault that was based on offset fold axes in seismic reflection profiles (Goldfinger et al., 1992). By combining the NSF, NURP, and NEHRP studies, we were able to map Fault B over a length of about 100 km, from the abyssal plain to the middle continental shelf and possibly to the inner shelf, if our preliminary interpretation is correct.

We were able to investigate the Coquille fault (Fig. 1, CF), initially located in 1992, in considerable detail during the 1993 NURP cruise. We mapped a very active NNW trending right-lateral strike-slip fault and associated folding that is currently deforming the sea floor in 1-2 m amplitude tight folds. The Coquille fault is in shallow (0-90 m) water, and there was little or no sediment cover other than coarse shell hash sand. Although we could not observe offset of young sediment, the active folding in the fault zone provided compelling evidence of Holocene motion on this fault. Additional evidence for late Quaternary activity comes from the Pleistocene sea cliffs near Bandon, Oregon, where the Coquille fault comes ashore. The lowest Pleistocene terrace is offset at this location, with dips up to 45° observed in the seacliff (A.R. Niem, pers. comm. 1993).

We also mapped the surface traces of a number of flexural slip thrust faults on the northwestern flank of Coquille bank (Fig. 1, CB). These faults are imaged in single channel reflection profiles, and are expressed at the seafloor. We mapped surficial scarps using DELTA and the AMS 150 kHz sidescan, and found scarps and "mole tracks" deforming Holocene olive grey mud and underlying grey Pleistocene clay.

An interesting discovery relating to all the faults observed during the 1993 field season is that the common methane-derived carbonate slabs found near all the faults show evidence of sudden breakage, even where observed on flat muddy bottom. We are considering the possibility that this breakage is the result of acceleration due to strong ground motion during large earthquakes. We may be able to devise an experiment to test the minimum acceleration needed to cause this breakage, and if so, will have an important clue to the magnitude of Holocene earthquakes on the Oregon margin.

4. Neotectonic Map of Washington Margin & Adjacent Abyssal Plain

We have completed 80% of the neotectonic map of the Washington continental shelf, slope and abyssal plain. It is being generated with the aid of Intergraph's MicroStation software for the Macintosh and SUN Sparc computer systems. A number of offsets in the deformation front off Washington and seismic reflection records from the abyssal plain were suggestive of the WNW-trending faults. As noted previously, we did acquire SeaMARC-IA sidescan images of three new left-lateral strike-slip faults on abyssal plain and accretionary prism off Washington using the new neotectonic map as a guide (Fig. 1, faults 7,8,9). A companion NOAA/NURP sidescan and
submersible study of these faults on the Oregon and Washington shelves is now funded for the summers of 1994 and 1995. Our NEHRP program will investigate the continental shelf extension of these faults and their potential impact on coastal bays.

Reports (also cited in text)


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Figure 1. General physiography of the Cascadia subduction zone, and locations of previously mapped (numbers 4, 5, and 6), and newly discovered (numbers 1-3 and 7-9) strike-slip faults in Oregon and Washington. Heavy lines represent approximate SeaMARC swath coverage. HB = Heceta Bank; DB = Daisy Bank; UF = Umpqua fault; CF = Coquille fault and CB = Coquille Bank. Arrow indicates Juan de Fuca plate motion and direction (062°) at 45°N latitude (DeMets et al., 1990). Base of continental slope is convergence boundary between Juan de Fuca and North American plates.
SURFACE RUPTURES PRODUCED BY THE JUNE 28, 1992 LANDERS, CALIFORNIA, EARTHQUAKE

9960-01623

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Investigations

Post-Earthquake studies of the June 28, 1992 Landers earthquake. Document the extent and magnitude of surface ruptures produced by the Landers event.

Results

Ruptures: Surface ruptures associated with the June 28, 1992 Ms 7.5 Landers earthquake extend discontinuously 100 km from the Little San Bernardino Mountains on the south to the Mojave Valley on the north. The ruptures occur along parts of six main north- to northwest-trending, sub-parallel faults (from south to north the Eureka Peak, Johnson Valley, Homestead Valley, Emerson, Camp Rock and Calico faults), and numerous north-trending secondary faults connecting or branching from them. The secondary ruptures occur in broad zones up to 15K wide between the the main ruptures. Most of the main faults were known prior to the Landers event, but most of the secondary connecting faults were unknown. Possibly, some of the secondary faults were produced by this earthquake. Southwest of the main rupture zone, minor surface rupture occurs on part of the Lenwood fault and on the newly mapped Upper Johnson Valley fault. Northeast of the main zone, minor rupture occurs on part of the Pisgah fault. In effect, the Landers earthquake was produced by complex rupture on numerous pre-existing and new faults in an area about 100km long and 40km wide.

Displacement along the main faults and most of the secondary faults is predominantly right lateral. However, ruptures branching from the main faults at angles greater than about 60° display extensional and left-lateral displacement. Horizontal displacement along the major faults is typically 1m to 3m, but on the Emerson fault it reaches 5.5m.
Horizontal displacement along the minor faults typically ranges from a few millimeters to 1m, but on the Kickapoo fault it reaches 3m. In some places along the main faults, horizontal displacement varies over short distances, generally dropping where secondary ruptures branch from the main ruptures. Summing horizontal displacements across the entire rupture zone yields a fairly smooth displacement profile with a maximum of about 6m on the Emerson fault and two prominent minima, one on the Home­stead valley fault, and the other on the Camp Rock fault. The Homestead minimum is probably real, but the Camp Rock minimum might be apparent, possibly reflecting incomplete data, not an actual decrease in horizontal surface displacement. The two minima suggest that the Landers earthquake consisted of three distinct rupture events.

Vertical displacement along the main faults is generally less than 0.3m, but reaches about 2m on the Emerson fault in the area of maximum horizontal displacement. In many places the sense of vertical displacement changes over short distances, and in some places it opposes general topographic relief. Shallow grabens occur in many places and over a broad range in size, from a few meters to at least one kilometer wide. Grabens typically occur between right-stepping rupture segments, and multiple-stepped half grabens occur where rupture segments curve northward. Horsts of various sizes occur between left-stepping rupture segments.

Surface ruptures along the major faults generally follow pre-existing topographic lineations and fault scarps. However, at two places on the Emerson fault, ruptures occur up to 20m from prominent late Quaternary fault scarps. This pattern suggests that Landers-type rupture events did not produce these scarps. Along the Kickapoo fault, ruptures connect a series of low geomorphic features, which in define a pre-existing fault zone. Most minor ruptures followed no pre-existing geomorphic features, suggesting relative youth for the faults along which they occurred. In many places, and on a wide range in scales, surface ruptures are discontinuous, consisting of simple to complex en-echelon fractures. However, where horizontal displacement exceeded about 1m, the rupture pattern is generally simple, narrowing to a continuous fracture or mole track. An exception is the Kickapoo fault, a series of en-echelon ruptures along which horizontal displacement reaches 3m. The complex pattern of the Kickapoo suggests that it is a relatively young feature connecting the Johnson Valley and the Homestead Valley faults. The relative complexity of the rupture at any given spot appears to reflect fault geometry and possibly rupture velocity, not rock type. Fault geometry and rupture patterns suggest that the velocity of the propagating rupture tip varied considerably. The rupture appears to have progressed as a series of short bursts rather than as a smooth, continuous tear.
The overall structural pattern of the Landers area, as expressed by gross lithology and geomorphology, is a series of northwest-trending lozenge-shaped horsts and grabens; the horsts form elongate mountain ranges granitic and metamorphic rocks, and the grabens form intervening valleys partially filled by sediment. This pattern is similar to that observed on much smaller scales in fault gouge and in highly sheared metamorphic rocks. This similarity suggests that the structural fabric of the Landers area is mature and of considerable age. The main, northwest-trending faults that partially ruptured in the Landers event bound several of the lozenge-shaped structures. However, the north-trending rupture zone of the Landers event cuts across this, northwest-trending structural fabric. The numerous minor connecting ruptures transfer slip from one main fault to another over broad zones cross mountain ranges and valleys. This pattern suggests that the Landers earthquake can be modeled either as a series of en echelon, right-lateral ruptures on parts of the main faults, or as a single, deep rupture that is discontinuously expressed on pre-existing faults at the surface.

Many, if not most, of the secondary ruptures branch from the main ruptures at high angles, generally greater than 60°. However, in many places the secondary ruptures curve to form more acute angles with the main ruptures. In some places, along the Emerson fault for example, secondary ruptures actually cross. The higher branching angles closer to the main ruptures probably reflect transitory dynamic stress near the propagating rupture tip, while the lower angles farther from the main ruptures probably reflect static regional stress. Most of the secondary ruptures branch northward off the main faults, indicating northward rupture propagation. With right-lateral displacement the ruptures had to propagate northward to produce the northward-branching pattern. However, secondary ruptures branch southward off the the southeastern part of the Homestead Valley fault, suggesting southeastward propagation along that fault segment.

On the Emerson fault the main rupture curves around the northeastern side of a fault-bounded mountain range, even though a more direct path would have been along the straighter, southwestern side of the range. The longer northerly route further suggests that the rupture propagated northward, but, more importantly, it raises the question of how the southeastern side of the range formed. Obviously, it had to be formed by southward-propagating ruptures. Southward rupture propagation may also have formed the prominent scarps along the Emerson fault that were not followed by the Landers rupture.
Techniques: The extent and complexity of the Landers rupture requires new techniques to gather and analyse rupture data; standard field and office techniques have proven inadequate. Unfortunately, this fact was not appreciated at the time of the earthquake, and as a consequence, much time, money and effort were wasted. More importantly, inferior and incomplete data were collected and an unparalleled opportunity was badly compromised, if not completely missed.

The USAF obtained 1:35K high-altitude (U-2) aerial photographs of the entire central Mojave Desert area within a few days after the Landers earthquake. Through a private contractor, the USGS obtained 1:6K aerial photographs along the main faults during the same period of time. Through the same contractor, PG&E obtained 1:4K photographs for two small areas about five months after the event; one of the areas covered the Kickapoo fault, and the other covered a series of unnamed faults in the Mojave Valley. The USGS further obtained 1:4K photographs for a small area between the Kickapoo and the southern part of the Homestead Valley faults about fifteen months after the event. Virtually all of the 1:6K and 1:4K photographs have been analysed under binocular microscope at 7 to 40 power (effective scales of 1:1000 to 1:100); standard stereoscopic techniques proved inadequate for the task. Some general technical conclusions follow:

1. A mosaic of the U-2 photographs (1:35K) provides an excellent overview of the Landers area and reveals most of the major ruptures, including a rupture along the the previously unknown Upper Johnson Valley fault. This rupture was not observed during field investigations following the earthquake.

2. The 1:6K photographs were used as a base for collecting slip and rupture data in the field following the earthquake. However, the scale proved too small for most mapping purposes. Enlargements of these photographs (1:3K to 1:1.5K) have proved very valuable in subsequent office investigations, and would have been much more useful than the original photographs in field.

3. More importantly, however, the ruptures should have been mapped in the office before slip data were collected in the field. Too much time was spent in the field locating and crudely mapping ruptures, and locating data stations. Conservatively estimated, over 90% of the ruptures subsequently mapped in the office using a microscope were missed during the field investigations immediately following the earthquake. More significantly, many geometric relationships, rupture patterns and rupture complexities were totally missed in the field. In effect, the initial field effort was a virtual waste of time. The field data could have been collected much more rapidly and accurately if the ruptures had been first been mapped on the photographs. Note that these startling conclusions are based on the subsequent analysis of admittedly inferior photographs!
Office studies and recent field checks reveal that the existing 1:6K and 1:4K photographs do not cover all the ruptures produced in the Landers event. Even 20x enlargements of the U-2 photographs do not reveal some minor, but extremely important ruptures that as late as 11/93 could still be seen clearly in the field. New photographs should be flown in several areas; contrary to the opinion of some people who obviously have not visited the Landers area recently, it is still possible to obtain useful aerial photographs. However, the window of opportunity for obtaining useful aerial photographs probably will be closed within the next few years.

Two-, three- and four-times enlargements of the 1:6K and 1:4K photographs (effective scales under the microscope of 1:150 to 1:300) reveal far more ruptures and greater detail than the contact prints. Slightly underexposed prints on glossy paper yield superior results at all scales. Unfortunately, all the original photographs were printed on flat-finished paper, and many were overexposed.

The tracings of the complex ruptures from the aerial photographs are of course distorted and cannot be accurately transferred to a scale-stable base by eye, the technique used in previous studies of earthquake ruptures. A computer-based procedure using commercial software has been devised to rectify each tracing, which then can be combined with tracings from adjacent photographs and ultimately transferred to a scale-stable base. Reference points for image rectification are obtained from stable map bases (standard quadrangles and orthophotoquads) and limited field surveys.

Ground photographs taken with a medium-format (60 x70mm) camera are extremely valuable in documenting and studying rupture displacements. Unfortunately, only a few such photographs have been taken, and financial and time constraints limit the number that will ever be taken of the Landers ruptures. A photographer should have systematically photographed all rupture within a few weeks after the earthquake.

Preliminary discussions with an expert in the field suggest that study of enhanced satellite imagery might be used to identify tectonic landforms in the semi-desert Landers area. Alluvial fan surfaces of different ages might provide a useful spacial and temporal context in which to interpret the Landers rupture pattern. Unfortunately, funding is not available for this valuable work.

Organization and Commitment: The extent and complexity of surface ruptures produced by the Landers earthquake are unparalleled in the published record. In this regard, the Landers event is unique, and is truly a world-class seismic event. Also, this earthquake occurred in a remote, semi-desert region with little cultural development. As consequence, the possibility of compiling a first-class data set is unparalleled. Unfortunately, the west-coast geologic community has failed in its responsibility make the best of this ephemeral opportunity. Primary responsibility to document the effects of this event as thoroughly as possible lies with SCEC. However, the SCEC compilation
at 1:24K is incomplete and extremely inaccurate. The USGS, with its man power, resources and mandate, should have stepped in to salvage the effort. Unfortunately, this did not happen. Many of the technical problems briefly alluded to above could have been detected and corrected if the USGS had made a serious commitment to document the surface ruptures at Landers in a thorough, accurate and expeditious manner. Instead, within a month after returning from the field, only one person was working on the project full time. Even worse, the compilation work done by most of the USGS personnel shortly after returning from the field was so incomplete and inaccurate that it is virtually useless. Part of this problem reflects the fact the field data were poorly collected in the first place (no slip vectors were measured, no data were collected or recorded systematically, etc), but at least half of the problem reflects indifference and incompetence of the compilers. No effort was made to rectify or even identify deficiencies and inaccuracies in the data set; the same situation produced the badly crippled and virtually useless USGS data sets from the last two California earthquakes that produced significant ground rupture. For the past year only one USGS employee has worked on the Landers ground-rupture project, and he volunteered! The crux of the problem is that, neither SCEC nor the USGS has set priorities that would insure the acquisition of a complete and accurate data set. For example, both SCEC and the USGS have heavily funded fault-trenching projects in the Landers area. These studies are important, but the trench sites will there for at least another four or five thousand years, while most of the surface ruptures probably won’t survive another four or five years. With the inability to set priorities, and the lack of individual and collective commitment, a useful ground rupture data set for the Landers earthquake will never be compiled. This is unfortunate because the entire project could have been completed in six to eight months if only four or five competent and dedicated people had been assigned to it, or had volunteered to work on it.

Publications:

None.
Geodetic Strain Monitoring

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Program element: II

Investigations

Two-color geodimeters are used to survey, repeatedly, geodetic networks within selected regions of California that are tectonically active. This distance measuring instrument has a precision of 0.1 to 0.2 ppm of the baseline length. Currently, crustal deformation is being monitored within the south moat of the Long Valley caldera in eastern California, across the San Andreas fault at Parkfield, California, at three locations near Palmdale, California on a section of the San Andreas fault that is within its Big Bend region, and at two locations near Pinon Flat, California. Periodic comparisons with other two-color geodimeters are conducted both at Parkfield and at Mammoth Lakes. These intercomparisons measurements serve as a calibration to monitor the relative stabilities of these instruments.

Results

1. Parkfield

Frequent measurements of length of 17 baseline are made for a geodetic network near Parkfield, California (Figure 1). Approximately one-half of these baselines straddle the San Andreas Fault along the segment that last ruptured in 1966. The data from these baselines are shown in Figure 2. This data are contaminated by both systematic dilatations due to drift in the instrument and localized displacements of monuments due to ground swelling from the seasonal rainfall. Computer routines have been written to remove systematic dilatations which can be compared with the periodic calibration measurements using the Parkfield based, two-color geodimeter and the portable, two-color geodimeter. Localized monument displacements have been removed by fitting the line-length changes to a function that is proportional to the rainfall measured previous to each distance measurement. This function is a linear combination of average rain in the period 0 to 2 days, 2 to 6 days, 6 to 14 days, 14 to 30 days, and so on. The results of removing both the instrumental dilatation and the rainfall response are shown in Figure 3. Although this method does a excellent job in removing the apparent seasonal variations, it could also contaminate the true line-length changes in
To address the issue of monument stability, we made arrangements with Frank Wyatt of UC San Diego to install additional monuments at two sites which have exhibited large seasonal variations. We have selected MIDE and POMO (Figures 1 and 2). The monument consists of 5, 10 to 15 meter long, 2.5 cm dia pipe where 4 of the pipes are installed into drill-holes oriented at 45° angles with respect to the ground’s surface, and the fifth pipe is vertical. All 5 pipes are welded together at a point 1 meter above the ground to establish rigidity. We expect to monitor the length changes from these two new sites and compare the changes from the existing monuments which are located less than 30 meters away.

2. Southern California

   Because of low funding to accomplish field work needed to measure our 5 networks in Southern California, we only made limited measurements. Specifically, we completed 2 surveys of Pinon Flat, 1 survey of Anza, 2 surveys of Pearblossom, 2 surveys of Buttes, and none at Palmdale.

3. Northern California, SF Bay

   We installed in mid-1993 a network shown in Figure 4 that straddles the junction between the Hayward, Calaveras, and Mission Faults. On a few baselines, we have the initial length measurements using the two-color geodimeter.

Publications

FIGURE 1. A map showing the locations of baselines measured at Parkfield using a two-color geodimeter. Measurements using the common station at CARR are made approximately 3 times each week.
FIGURE 2. Plot of two-color geodimeter data for measurements of line-length changes using the common station at CARR at Parkfield. A linear trend with time has been fit to the line-length changes, and the residuals from that fit are plotted. The value of the secular rate is shown next to the baseline name.
FIGURE 3. Same as Figure 2 but the data has been adjusted for systematic dilatations due to instrument problems and localized displacements of the monuments using an algorithm described in the text.
FIGURE 4. Map showing the network of geodetic baselines installed in the SF Bay area to examine the transfer of slip between the Calaveras and Hayward faults.
Parkfield Prediction Experiment

9960-12246

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Program element II

Investigations

This project coordinates the different experiments at Parkfield run by both USGS and non-USGS investigators. Some of the experiments are focused on the prediction in the short-term of the next Parkfield earthquake. Other experiments will document pre-seismic, the co-seismic, and post-seismic events. Both data from seismicity and from deformation are examined for significant events. This project has been examining the formal rules used in either calling an "alert" or "status-level".

Results

1. Significant Signals

The table summarizes the events in the past 1.75 years that meet established criteria to be called either an "alert" or "x-level status". For purposes of semantics, low-level signals which meet the "C" and "D" levels are called "status-levels", and the larger signals which meet the "A" and "B" levels remain as "alerts".

2. A-level alert of October 1993

In mid-October, 1992, the Parkfield earthquake experiment had its first A-level alert where we advised the CA. Office of Emergency Services of a significant likelihood of a M6 earthquake at Parkfield. We have published our data leading to the alert in the March 1993 issue of EOS.

3. NEPEC review

An independent review panel appointed by NEPEC examined the Parkfield earthquake prediction experiment and published their criticisms in a USGS Open File report (NEPEC, 1993). They concluded that in spite of the uncertainties of the forecast statistics, Parkfield is the most likely place to capture an earthquake and that the data obtained will provide a high scientific return on our investment. The panel made several general suggestions to improve the experiment (more specific suggestions are in the text).
USGS should continue experiment and give it high priority
- Need long-term plan to replace obsolete and failed equipment
- Acquire control of land where instruments are located to avoid disruption due to landowners change.
- Continue public policy side of experiment

4. Publications


### Table. 1992 Parkfield alerts.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Description</th>
<th>Size</th>
<th>Level</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>920127</td>
<td>Middle Ridge</td>
<td>Creep Event</td>
<td>0.9 mm</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>920127</td>
<td>Middle Mountain</td>
<td>Creep Event</td>
<td>0.9 mm</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>920224</td>
<td>Gold Hill</td>
<td>Earthquake</td>
<td>M 2.5</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>920404</td>
<td>Middle Mountain</td>
<td>Earthquake</td>
<td>2 M &gt; 1.1</td>
<td>D</td>
<td>originally missed</td>
</tr>
<tr>
<td>920420</td>
<td>Middle Ridge</td>
<td>Creep Event</td>
<td>1 mm RL</td>
<td>D</td>
<td>Strain changes at Froelich</td>
</tr>
<tr>
<td>920420</td>
<td>Middle Mountain</td>
<td>Water well</td>
<td>13.7 cm drop</td>
<td>D</td>
<td>familiar combo</td>
</tr>
<tr>
<td>920529</td>
<td>Gold Hill</td>
<td>Earthquake</td>
<td>M 3.2</td>
<td>D</td>
<td>Strain change at GH</td>
</tr>
<tr>
<td>920603</td>
<td>Middle Mountain</td>
<td>Earthquake</td>
<td>M 1.5</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>920916</td>
<td>Gold Hill</td>
<td>Earthquake</td>
<td>M 2.5</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>921001</td>
<td>Froelich</td>
<td>Strain</td>
<td>Max of 1.6 mm</td>
<td>C</td>
<td>Adjacent sites, response to creep</td>
</tr>
<tr>
<td>921001</td>
<td>Middle Mtn.</td>
<td>Water well</td>
<td>M 1.5</td>
<td>D</td>
<td>extends alert</td>
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<tr>
<td>921004</td>
<td>South end MM</td>
<td>Earthquake</td>
<td>M 2.7</td>
<td>C</td>
<td></td>
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<tr>
<td>921005</td>
<td>South end MM</td>
<td>Earthquake</td>
<td>M 2.4</td>
<td>C</td>
<td>extends C-level</td>
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<tr>
<td>921007</td>
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<td>Earthquake</td>
<td>M 2.5</td>
<td>D</td>
<td></td>
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<tr>
<td>921020</td>
<td>South end MM</td>
<td>Earthquake</td>
<td>M 4.7</td>
<td>A</td>
<td>Co-seismic steps</td>
</tr>
<tr>
<td>921020</td>
<td>Flinge Flat</td>
<td>Water Well</td>
<td>2 cm</td>
<td>D</td>
<td>no affect on A-level</td>
</tr>
<tr>
<td>921023</td>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>Step-down from A-level</td>
</tr>
<tr>
<td>921026</td>
<td>South end MM</td>
<td>Earthquakes</td>
<td>M 3.4 &amp; 3.9</td>
<td>B</td>
<td>2 km NW of M4.7</td>
</tr>
<tr>
<td>921028</td>
<td>South end MM</td>
<td>Earthquake</td>
<td>M 1.9</td>
<td>C</td>
<td>2 events in 72hrs</td>
</tr>
<tr>
<td>921113</td>
<td>XMD1, MM</td>
<td>Creep</td>
<td>1.1 mm</td>
<td>D</td>
<td></td>
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<tr>
<td>921116</td>
<td>Slack Canyon</td>
<td>Earthquake</td>
<td>M2.45</td>
<td>C</td>
<td>Creep and eq in 72hrs</td>
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<td>921121</td>
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<td>Earthquake</td>
<td>M1.5</td>
<td>D</td>
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<tr>
<td>921222</td>
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<td>Earthquake</td>
<td>M1.7</td>
<td>D</td>
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<td>Earthquake</td>
<td>M3.4</td>
<td>C</td>
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</tbody>
</table>

Note. Right lateral creep, water level rises, and compressive strain are positive.

1992 Combined Alert Totals: 1 A alert 1 B alert, 5 C alert, 12 D alerts.

Total alerts since beginning experiment: 1 alert 2 B alert, 35 C alerts, 97 D alerts.

### Table. 1993 Parkfield alerts.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Description</th>
<th>Size</th>
<th>Level</th>
<th>Comments</th>
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<td>D</td>
<td>2 events in 72hrs</td>
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<tr>
<td>930125</td>
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<td>Earthquake</td>
<td>M2.5</td>
<td>C</td>
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<tr>
<td>930126</td>
<td>Simmler</td>
<td>Earthquake</td>
<td>2.5</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>930304</td>
<td>Middle Mtn.</td>
<td>Creep</td>
<td>0.6mm</td>
<td>D</td>
<td>at XMMI</td>
</tr>
<tr>
<td>930304</td>
<td>Middle Mtn.</td>
<td>Water Well</td>
<td>12.6 cm</td>
<td>D</td>
<td>familiar combo</td>
</tr>
<tr>
<td>930313</td>
<td>Middle Mtn.</td>
<td>Earthquake</td>
<td>M3.5</td>
<td>D</td>
<td>Same loc. as 921026</td>
</tr>
<tr>
<td>930313</td>
<td>Parkfield</td>
<td>2-color</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>930316</td>
<td>Parkfield</td>
<td>2-color</td>
<td>D</td>
<td></td>
<td>continuation</td>
</tr>
<tr>
<td>930403</td>
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<td>Earthquake</td>
<td>M4.4</td>
<td>B</td>
<td>2 km shallower than 921020</td>
</tr>
<tr>
<td>930406</td>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>step-down from B</td>
</tr>
<tr>
<td>930408</td>
<td>Middle Mtn.</td>
<td>Earthquake</td>
<td>M2.9</td>
<td>C</td>
<td></td>
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<tr>
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<td>M+2.4</td>
<td>C</td>
<td>2 events</td>
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<tr>
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<td>Creep</td>
<td>0.7 mm</td>
<td>D</td>
<td>at XMMI</td>
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<td>M3.1</td>
<td>C</td>
<td></td>
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<td>&lt;1 mm</td>
<td>C</td>
<td>2 events &gt;0.5 in 1 hour at XMD1 &amp; XMM1</td>
</tr>
<tr>
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<td>D</td>
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<td>Slack Canyon</td>
<td>Earthquake</td>
<td>M2.5</td>
<td>D</td>
<td>PKF region</td>
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<td>930812</td>
<td>Middle Mtn.</td>
<td>Earthquake</td>
<td>M1.5</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>930822</td>
<td>Middle Mtn.</td>
<td>Water Well</td>
<td>-6.5 cm</td>
<td>D</td>
<td>minor creep xmd1</td>
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<tr>
<td>930823</td>
<td>Middle Mtn.</td>
<td>Earthquake</td>
<td>M1.2</td>
<td>C</td>
<td>2 events and combo rule</td>
</tr>
<tr>
<td>930827</td>
<td>Middle Mtn.</td>
<td>Earthquake</td>
<td>M1.9</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>930927</td>
<td>Gold Hill</td>
<td>Earthquake</td>
<td>M3.5</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>930929</td>
<td>Middle Mtn.</td>
<td>Water Well</td>
<td>4.7 cm</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

Note. Right lateral creep, water level rises, and compressive strain are positive.

1993 Combined Alert Totals: 0 A alert 2 B alert, 7 C alert, 12 D alerts.

Total alerts since beginning experiment: 1 A alert 4 B alert, 42 C alerts, 109 D alerts.
Investigations

The primary focus of this project is the development of state-of-the-art computation for analysis of data from microearthquake networks. For the past twelve months I have been involved in:

(1) **Testing a Digital Telemetered Seismic Array (in conjunction with Gray Jensen)**. Software for data acquisition and processing for the USGS digital telemetered seismic array was completed this summer under my supervision. Four three-component digital seismic stations were set up in the San Francisco Bay area for testing purposes. The system has been in operation since October, 1993, and has performed successfully.

(2) **Design and Implementation of a Prototype Earthquake Warning System for Taiwan**. Under a cooperative program between USGS and the Taiwan Central Weather Bureau, a prototype earthquake warning system has been designed and are being implemented now. A modern digital seismic network with rapid response time (10 - 20 sec after an earthquake occurred) is under construction in the Hualien area of Taiwan by Nanometrics of Canada under my supervision. At the same time, Quanterra is under contract to supply three broad-band digital seismic stations of our specification. The Hualien network and the broad-band stations are expected to be in operation by summer of 1994.

Reports


Investigations

1. In 1966 a seismographic network (CALNET) was established by the USGS to monitor earthquakes in central California. In the following years the network was expanded to monitor earthquakes in most of northern and central California, particularly along the San Andreas Fault, from the Oregon border to Santa Maria. In its present configuration there are over 350 stations in the network, and more than 60 of those consist of more than one component. Also recorded are signals from more than 60 stations operated by other agencies or institutions, including the University of California, Berkeley, the University of Nevada, Reno, the California Institute of Technology, the California Department of Water Resources, and the Lawrence Livermore National Laboratory. The primary responsibility of this project is to monitor, process, analyze, and publish seismic data recorded from this network.

2. This project maintains a seismic data base of CALNET data for the years 1969 to the present on both computers and magnetic tapes for those office staff who are doing research using the network data.

3. Project staff often act as the primary spokesperson or authority when inquires are received from the press, the public, or scientists from both inside and outside the Geological Survey regarding earthquakes that have been recorded by the network. Inquires include simple questions about recent earthquakes in the region, such as the date and time of occurrence, the location, and the magnitude of the earthquake. Or they may be somewhat complex and require expert opinion or interpretation, such as the relationship of recent swarms of earthquakes to historical seismicity, and how each relates to the seismogenic potential of a region or fault.

4. As time permits research projects are undertaken by project personnel on some of the more interesting or unusual events or sequences of earthquakes that have occurred within the network, or related topics.

Results

1. Figure 1 illustrates most of the 19181 earthquakes located in northern and central California and vicinity during the time period October 1992 through September 1993. There were several significant earthquakes and their aftershocks that affected the network during that time period. The largest earthquake recorded was a M6.1 event on May 17 at 4:20 pm PDT that was located approximately 47 kilometers east of Big Pine in the Eureka Valley. It was followed by several hundred aftershocks, including 10 that were magnitude 4.0 or larger. Since that region is very sparsely populated the impact of those earthquake on residents was minimal.
On September 21 at 8:28 pm PDT a magnitude 5.6 earthquake occurred in southern Oregon, approximately 30 kilometers west-northwest of Klamath Falls. It was followed at 10:45 pm by a magnitude 5.8 shock in nearly the same location. Hundreds of aftershocks followed those quakes, and are still occurring. Most of the events that were magnitude 2.0 or larger were located by this office, as well as the University of Washington in Seattle. Included in that swarm were at least 8 magnitude 4 aftershocks, all during the month of September. Four new stations were installed to help in the location efforts, two of which are telemetered to Menlo Park. The quakes were felt throughout the region, and there was damage to several buildings in Klamath Falls, and one death just north of that city. That is a region of typically low seismicity so the earthquakes were very unusual.

Work was completed the catalog of earthquakes for 1992. The effort was largely spearheaded by David Oppenheimer with many branch members making significant contributions. Work is currently underway on preparing 1993 data for publication, hopefully early in 1994.

2. The 1993 catalog is relatively complete and correct through October. We are currently adding events for August through October that were missed in the routine CUSP detection and processing. Those earthquakes are mostly smaller than magnitude 3.0. Quarry blasts still need to be identified for August through November.

3. More than 55 requests were received for seismic data which required computer searches of the data base. Most of the searches were for specific regions and time periods. Some were more complex requiring multiple searches and some interpretation. Data from these searches were most often distributed as printed listings, but but some were also sent as data files over electronic mail, on magnetic tape, and floppy disk.

Telephone inquires were handled at a rate of two to four per day. Most of these required verbal responses that were of short duration, 10 minutes or less. The majority of these were simple requests for information about recent earthquakes, ongoing or past USGS research, maps and publications, and some interpretation of geologic information. During periods of higher than normal seismic activity the project may receive as many as 20 to 30 requests of this type per hour.

Recognition of earthquake risk and related hazards has increased dramatically since the Loma Prieta earthquake of October 1989. A consequence of this has been an increase in insurance claims related to earthquakes that has resulted in an increase in insurance company requests for data searches for recent earthquake activity. Another consequence of that earthquake is the increasingly common request from homeowners or potential homeowners for information about all types of geologic hazards, particularly earthquake hazards, in the area around their homes or where they plan to purchase a home.

4. None of the staff was able to pursue any research studies as the high rate of seismicity for the period kept everyone busy.

Reports

Figure 1. Seismicity for October 1992 - September 1993
Investigations

Determine slip rates and earthquake recurrence times on San Andreas and Hayward Faults. Compare rates of geologically determined surface slip to rates of historic creep and geodetically determined deep slip. Analyze effects of structural complexity and fault segmentation upon inferring recurrence from slip rate.

Results

1. Creep Rates, Hayward Fault. We confirmed and revised the interesting results on creep rate for the initial 3 years (1989-1992) of precision monitoring of about 20 arrays established for observing afterslip expected in the next major earthquake on the Hayward Fault [Lienkaemper, Gatehouse, and Simpson, 1993]. Creep rate along most of the fault since the 1989 Loma Prieta Earthquake (LPE) until summer of 1992 averaged only 70 ± 10 percent of the long-term rate. At the southeast end where long-term rates have been about 9 mm/yr right-lateral, the post-LPE creep rate continues until December 1993 at 0-2 mm/yr left-lateral. This reversal in the direction of creep rate is a predictable effect of modelled static stress changes and can be expected to continue for at least another 2 years at our southernmost array. From central Fremont northward, creep rate has at most sites returned to normal (where long-term rate is 5-6 mm/yr), but at some sites creep is still retarded (where long-term rate is 3.5-5 mm/yr).

2. Holocene Slip Rates, Masonic Site. A serious problem at the NSF AMS facility delayed completion of this project, however age dating is now completed. Preliminary report is Lienkaemper and Borchardt [1993].

3. Hayward fault, telemetered creepmeter siting and installation with R.G. Bilham and K.S. Breckenridge. We chose several sites for a 3-yr installation program that began in November-December 1993 with installation of the first device in southern Fremont using 30-m deep concrete piers that will also be monitored for pier tilt.
Reports


Investigations

The principal subject of investigation was the measurement and analysis of crustal deformation within tectonically active areas of the United States. In Table 1 we list the networks surveyed during FY 1993 along with details about the data collected by personnel from the Crustal Strain project.

Nearly all measurements were made with Global Positioning System (GPS) receivers. Only 15 lines in the Yucca Mountain network and 3 in the Loma Prieta Monitor network were measured with the Geodolite (a single-frequency laser distance meter). In addition, we resurveyed a 15 km-long, first-order level network on Middleton Island, in the Gulf of Alaska.

GPS surveys in Alaska were funded by NEHRP-PN, NASA’s DOSE program, and DSC (through AVO’s Katmai Project). DOSE provided operating expenses for the establishment and survey of the Prince William Sound GPS network. DSC provided operating expenses for the survey of the Katmai GPS network. Salaries for work in Alaska were provided by NEHRP-PN.

Several projects were cooperative efforts with other projects or outside agencies. All data, except that from the Basin and Range experiment was archived and reduced by personnel from the Crustal Strain project. The resurvey of the 130-station L.A. Basin GPS network was organized by Ken Hudnut and involved field parties from Orange, Riverside, San Bernardino, and L.A. counties, the City of Los Angeles, the Metropolitan Water District, and the Crustal Strain project. Ken Hudnut also organized a survey of several fault crossing GPS arrays at the northern end of the Coachella Valley, with field work performed by crews from Riverside County and the Crustal Strain project. The survey of the Mammoth and Mono Chain GPS networks was made cooperatively with the Modeling and Monitoring Crustal Deformation project (Ross Stein). The establishment and survey of the Willapa GPS network was a cooperative project with CVO (Dan Dzurisin). The Crustal Strain project occupied a station in Neah Bay, Washington, to support a sea-floor geodesy experiment conducted by NASA’s Jet Propulsion Laboratory, Scripps, and the Geologic Survey of Canada.
We continue to monitor post-seismic strain diffusion with GPS surveys of the Loma Prieta profile, the Landers profile, and the Cape Mendocino network.

The array of continuously recording GPS receivers in northern California began expanding in 1993. The network is a cooperative effort between the USGS, University of California at Berkeley (Barbara Romanowicz, Rich Clymer), Lawrence Livermore (Shawn Larsen), and Trimble Navigation (Brian Frohring). The USGS has operated two codeless Ashtech receivers located near the Hayward fault since September 1991. UC Berkeley installed one P-code Ashtech receiver near the Hayward fault in August 1993, and another at Columbia (a broadband seismic station in western foothills of the Sierra Nevada Mountains) in December 1993.

### Table 1. Field Surveys FY 1993

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Totals 4 133 34 18 647 32 425 23 10
In October 1993 Trimble Navigation installed two P-code SSE receivers near the Hayward fault, at sites chosen and constructed by USGS. Eventually there will be a nine-station continuous array in northern California. There will be five stations near the Hayward fault. The other four stations will be Farallon Islands, Arcata, Parkfield, and Columbia.

**GPS Data Reduction and Data Archives**

We are evaluating GIPSY-OASIS II (JPL), GAMIT (MIT and Scripps), and Bernese v. 3.4 (University of Berne) GPS data reduction software. We are converting our GPS data processing from Bernese v. 3.2 as implemented on Macintosh computers to one or more of the above packages running on UNIX workstations. We plan to use Bernese v. 3.4 primarily to update solutions obtained with version 3.2. Ken Hudnut, in the Pasadena office, reduces all his GPS data with GAMIT. Mark Murray in Menlo Park reduces the Pacific Northwest data with GAMIT. GAMIT offers a complete data reduction-analysis package, the best interactive data editing, and robust handling of old and poor data. Interactive data editing, however, can be very time consuming. Nancy King is testing the GIPSY-OASIS II software with data from the continuously recording Hayward network. GIPSY offers us the most automation and the best data reduction algorithms, but it requires the most computer resources (CPU time, memory, and disk space). Data reduction is greatly simplified now that precise orbits are available from several sources and improved, automatic data-cleaning algorithms are in use. The majority of our data, however, is collected with codeless receivers (C/A code on the L1, codeless on L2), and often contains cycle slips not repaired by automatic data-cleaning algorithms. With our current receivers we do not expect to achieve complete “hands-off” automation even with GIPSY.

We are developing a UNIX database for easy data retrieval and inspection. As of December 1993, raw and RINEX data files for 1993 and most of 1992 are on optical cartridges, and can be made available upon request. An index file for the raw data is available now, via anonymous FTP, in directory /pub/outgoing/gpsdata on the USGS machine andreas.wr.usgs.gov (IP 130.118.4.120). This index gives campaign name, station name, 4-character code, raw and RINEX file names, start and end times, file length, sample interval, station position, receiver type, and comments for each raw data file. The index is complete for all of 1993 and most of 1992. We have also submitted our most recent data from southern California to the SCEC archive. Eventually all our data will be available via anonymous FTP from the USGS-UC Berkeley data archives. For more information, send e-mail to kwendt@isdmnl.wr.usgs.gov.

**Results**

1. *Postseismic Deformation Following the 1989 (M_s = 7.1) Loma Prieta, California, Earthquake*

Postseismic deformation along a 90-km profile bisecting the projected surface trace of the coseismic rupture of the 1989 Loma Prieta earthquake has been monitored by frequent GPS surveys for 3.3 years following the earthquake. In addition to the expected deformation associated with secular strain accumulation on the San Andreas and Calaveras faults, deformation associated with postseismic readjustment has been detected. Most of that deformation can be attributed to 1.5 m right-lateral and 0.9 m reverse postseismic slip on a 5-km-wide downdip extension of the Loma Prieta rupture.
In addition there seems to be a 0.1 m postseismic collapse of the Loma Prieta rupture zone in the direction perpendicular to the plane of the rupture. Postseismic collapse of the Loma Prieta rupture zone is also suggested by the focal mechanism of the Loma Prieta aftershocks, which indicate a postseismic stress state dominated by fault normal compression. The fault-normal (N48°E) surface displacements plotted as a function of time exhibit a curvature suggesting a relaxation time of about 1.4 yr. Similar plots of the fault-parallel (N42°W) displacement components do not exhibit significant curvature. Presumably, those plots are dominated by secular strain accumulation along the San Andreas and Calaveras faults rather than postseismic relaxation.


Over the decade 1983–1993 the U.S. Geological Survey has measured the deformation of a 50-km-aperture trilateration network centered on Yucca Mountain, the proposed disposal site for high-level nuclear waste in the United States. The network was surveyed in 1983, 1984, and 1993. The average annual principal strain rates are $0.010 \pm 0.020 \mu \text{strain/yr N90°W} \pm 2°$ and $-0.009 \pm 0.021 \mu \text{strain/yr N00°E} \pm 2°$, indicating no significant strain accumulation. The southeast corner of the network was disturbed on June 29, 1992, by the Little Skull Mountain earthquake ($M_s = 5.4$), the epicenter of which is about 20 km southeast of the Yucca Mountain site. Using the seismically determined fault plane (dip 54° S55°E), we find that 0.580 ± 0.075 m of normal slip on a 5 km square rupture surface at a depth of about 8 km provides a good fit to the observed deformation in the southeast corner of the network. The inferred seismic moment is $(4.4 \pm 0.6) \cdot 10^{17} \text{N-m}$ which compares well with the observed seismic moment of $4.1 \cdot 10^{17} \text{N-m}$.

3. Strain Accumulation Along the Laguna Salada Fault, Baja California, Mexico

Strain accumulation observed over the 1978–1991 interval in a 30 x 100 km aperture trilateration network spanning the Laguna Salada fault is described by the principal strain rates $0.101 \pm 0.012 \mu \text{strain/yr N80°E} \pm 2°$ and $-0.021 \pm 0.012 \mu \text{strain/yr N10°W} \pm 2°$, extension reckoned positive. These strain accumulation rates have been corrected to remove coseismic effects of the nearby 1979 Imperial Valley ($M = 6.5$), 1980 Victoria (Baja California) ($M = 6.4$), 1987 Superstition Hills ($M = 6.5$), and 1987 Elmore Ranch ($M = 5.9$) earthquakes. The observed strain rates indicate extension at a rate of about 0.08 $\mu \text{strain/yr}$ perpendicular to the trend (N35°W) of the Salton trough as well as a right-lateral tensor shear strain rate 0.05 $\mu \text{strain/yr}$ across it. The extension perpendicular to the trough is observed neither farther north near the Salton Sea nor farther south across the Gulf of California. However, Holocene slip on the Laguna Salada fault, about equal parts right-lateral and normal slip, is consistent with the observed strain accumulation. A simple dislocation model intended to explain the observed strain accumulation as a product of slip at depth on the fault requires that the Laguna Salada fault be listric.

4. Probability of One or More $M \geq 7$ Earthquakes in Southern California in 30 Years

Eight earthquakes of magnitude greater than or equal to seven have occurred in southern California in the past 200 years. If one assumes that such events are the product of a Poisson process, the probability of one or more earthquakes of magnitude seven or larger in southern California within any 30 year interval is $67\% \pm 23\%$ (95% confidence
Because five of the eight $M \geq 7$ earthquakes in southern California in the last 200 years occurred off of the San Andreas fault system, the probability of one or more $M \geq 7$ earthquakes in southern California but not on the San Andreas fault system occurring within 30 years is $52\% \pm 27\%$ (95% confidence interval).

5. **Deformation Across the Alaska-Aleutian Subduction Zone Near Kodiak, Alaska**

![Figure 1](image)

Figure 1. a) Average velocities relative to Karluk. Vectors are tipped with 95% confidence ellipses. Dotted lines show the NUVEL-1 predicted direction of convergence between the Pacific and North American plates. The anomalous vector on the southern end of the Alaska Peninsula results from a suspect measurement in 1989. b) Observed and modeled velocities as a function of distance from the Alaska-Aleutian trench. Error bars are ±1 sd. We use a dip of 5°, depth to the top of 6 km, a convergence rate of 61 mm/yr, and downdip widths of 150 and 175 km.

A 10-station GPS profile surveyed in 1989, 1991, and 1993 extends for 300 km from offshore of Kodiak Island across the Alaska Peninsula near the southwestern end of the rupture of the 1964 $M_{w} 9.2$ Prince William Sound earthquake. Near Kodiak Island NUVEL-1 predicts that the Pacific plate is converging upon the North American plate in a N25°W direction at a rate of 61 mm/yr. Average velocities relative to the central station Karluk (Figure 1a) show 35 mm/yr of distributed NNE contraction across the network, with a minor amount of trench parallel shear. The velocities in the convergence direction (Figure 1b) are consistent with that predicted by a dislocation model for subduction zones proposed by Savage (JGR, p. 4984–4996, 1983). The 5° dip of the main thrust zone was determined by seismic refraction. A locked plate interface with a down-dip width of 175 km provides a good fit to the observed deformation. This width
is consistent with the extent of the 1964 rupture as indicated by the hinge line of the
elevation changes that accompanied the earthquake.

6. **Empirical Earthquake Probabilities From Observed Recurrence Intervals**

The probability $p$ that a given fault segment will rupture within a specified time $T$
following the preceding rupture is evaluated empirically from a sample of observed
recurrence intervals for that fault segment. All that is assumed is that the probability
of rupture within the specified time interval is the same for all rupture cycles on that
segment. Suppose that $m$ of the $n$ observed recurrence intervals correspond to cycles
in which rupture occurred within the interval $T$ following the preceding earthquake.
The probability density that rupture in the current cycle will also fall within the
interval $T$ following the most recent earthquake is then given by the beta distribution
$\hat{P}(p|m,n) = \{(n + 1)!/[m!(n - m)!]\} p^m (1 - p)^{n-m}$. The best estimate of the desired
probability $p$ is $\langle p \rangle = (m+1)/(n+2)$, and a measure of the breadth of the distribution
is the standard deviation $\sigma = [\langle p \rangle (1 - \langle p \rangle)/(n+3)]^{1/2}$. Because it is unlikely
that the number $n$ of observed recurrence intervals will be much greater than 10, the
probability generally will not be defined more closely than $\pm 0.2$. Moreover, increasing
$n$ decreases the uncertainty only very slowly.

7. **Coseismic Deformation of the April 25, 1992 Cape Mendocino, California, Earthquake**

(These results are from a joint project with Grant Marshall and Ross Stein.) We invert
coseismic surface displacements derived from Global Position System (GPS), leveling,
and coastal uplift to determine a finite-fault geometry and uniform-slip model for the
April 25, 1992 $M_s = 7.1$ Cape Mendocino earthquake. Horizontal and vertical relative
displacements of 14 monuments are derived from GPS surveys conducted in 1989, in
1991 following the $M_s = 6.2$ Honeydew earthquake, and in 1992 one month after the
mainshock. The horizontal displacements are corrected for secular strain accumulation
Section elevation differences between 29 monuments are measured by spirit leveling
surveys conducted between 1935 and 1992. Coastal uplift with respect to mean sea level
of 12 coastal sites south of Cape Mendocino is measured by the die-off of intertidal
marine organisms (Carver and others, submitted to Geology). Maximum observed
displacements are 0.4 m horizontal and 1.4 m uplift along the coast. We use a Monte
Carlo approach to estimate an optimal fault geometry and slip. For each trial, the seven
parameters describing the geometry of the rectangular dislocation are randomly varied
and the slip vector that minimizes the residual chi-square of the coseismic displacements
is linearly estimated. We use an F-ratio test to assess which models are statistically
consistent with the best-fitting model. This approach allows us to thoroughly examine
the range of model faults and to assess the uncertainties and correlations associated with
the optimal model parameters. The optimal uniform-slip model has a standard deviation
of unit weight of 4.2 and provides a reasonable fit to geodetic observations. Our optimal
model resolves 4.8 m of slip on an $13 \times 16$ km rectangular fault that dips $28^\circ$SE. The
fault extends from 1.5 to 9.0 km in depth and projects to the mainshock hypocenter.
The location of the fault plane reasonably matches the observed aftershock locations
horizontally, but lies several kilometers above them. Assuming an inhomogeneous elastic
half-space with more compliant materials lying above the fault surface may decrease this
discrepancy. The orientation of the slip vector, which is nearly parallel to the estimated North America-Juan de Fuca relative plate motion, and the fault location and orientation suggest that the 1992 Cape Mendocino earthquake is the first well-recorded event to rupture the Cascadia subduction zone megathrust. The uplift predicted by our model matches areas with high Quaternary uplift rates. Therefore, it is plausible that repeated ruptures in the past of this southernmost segment of the Cascadia megathrust are at least partly responsible for the growth of the geologic structures in the area. If we assume the $M_s = 7.1$ Cape Mendocino event is a characteristic earthquake for this segment, a comparison of our estimated horizontal slip vector with plate convergence rates predicts a characteristic repeat time for this event of 130 years, with a 75% confidence range between 100-200 years. Comparing our predicted uplift with coastal uplift rates estimated from Holocene marine terraces also predicts a 200-year repeat time.

8. Coseismic Slip Distribution of the Landers Earthquake

J. Freymueller (Stanford), N.E. King, and P. Segall (Stanford) derived a model for the coseismic slip distribution on the faults which ruptured during the Landers earthquake sequence of 29 June 1992. The model is based on the inversion of surface geodetic measurements, primarily vector displacements measured with GPS. The inversion procedure assumes that the slip distribution is to some extent smooth. For a given fault geometry a family of solution of varying smoothness can be generated. We prefer the smoothest model which does not significantly increase the misfit to the data. The geodetic model should also agree with the observed surface slip. Solutions which give roughly equal weight to misfit and smoothness meet these criteria and have certain features in common: (1) there are two main patches of slip, on the Johnson Valley fault, and on the Homestead Valley, Emerson, and Camp Rock faults, (2) virtually all slip is in the upper 10-12 km, (3) the model reproduces the geologically measured surface displacements to a reasonable degree, without prior constraint on the surface slip. In all models regardless of smoothing, very little slip occurs on the fault representing the Big Bear event, and the total moment of the Landers event is $9 \times 10^{19} N \cdot m$.

9. Continuous GPS Across the Hayward Fault

The U. S. Geological Survey began continuous GPS monitoring in September 1991. A nearly north-south 8.1 km baseline crosses the Hayward fault near Lake Chabot. This segment of the fault last ruptured in a major earthquake in 1868, and is now a zone of high seismicity and creep. We operate codeless dual-frequency Ashtech LM-XII receivers at 30 second sampling, archive daily files, clean up the data using PhasEdit (Jeff Freymueller, Stanford University) and process seven-hour sessions with the Bernese version 3.2 software. Figure 2 shows the vector components of the station west of the Hayward fault (Winton) relative to the station east of the fault (Chabot). Not shown are six offsets in the time series that we determined by solving simultaneously for slope, intercept, and offsets in a least squares adjustment. Three offsets resulted from moving antennas at one or both sites. The first two were recenterings. The third was a change to a fixed centering mount at both sites. The other offsets resulted from receiver or antenna swaps or firmware upgrades. These observed offsets are only a few mm, but they suggest that systematic error may arise from changes in equipment or firmware.
The rms scatter about the best linear fit is 2.2 mm in the north, 2.9 mm in the east, 11.1 mm in the vertical, and 2.1 mm in baseline length. The rates of change (Winton relative to Chabot) are $2.9 \pm 0.2$ in the north, $-8.1 \pm 0.3$ in the east, $-9.9 \pm 0.9$ in the vertical, and $-0.7 \pm 0.2$ in baseline length. The vertical rate of change is difficult to understand.

Figure 2. Length and vector components as a function of time for the 8.1 km baseline between the continuously recording GPS receivers near the Hayward fault. Uncertainties are one standard deviation as derived from the rms scatter about a weighted linear fit.

10. *Strain Accumulation in the Shumagin Islands: Results of Initial GPS Measurements*

Deformation in the Shumagin seismic gap has been monitored with repeated trilateration (EDM) in the 1980–1987 interval and with the Global Positioning System (GPS) in 1987–1991 interval. The geodetic network extends for 100-km across the Shumagin Islands to the Alaska Peninsula. Results from the GPS surveys are consistent with those previously reported for the EDM surveys: we failed to detect significant strain accumulation in the N30°W direction of plate convergence. Using the method of simultaneous reduction for position and strain rates, we found the average rate of extension in the direction of plate convergence to be $-25 \pm 25$ nanostrain/yr during the 1987–1991 interval of GPS surveys compared with $-20 \pm 15$ nanostrain/yr during the 1981–1987 interval of complete EDM surveys. We found a marginally significant $-26 \pm 12$ nanostrain/yr extension rate in the 1981–1991 interval covered by the combined EDM and GPS surveys. Strain rates are higher, but not significantly so, in the part of the network closest to the trench. Spatial variation in the deformation is observed in the 1980–1991 average station velocities, where three of the four stations closest to the trench have an arcward velocity of a
few mm/a. The observed strain rates are an order of magnitude lower than the \(-200\) nanostrain/yr rate predicted by dislocation models.

11. *Crustal Deformation in the Northern San Francisco Bay Area from GPS and Geodolite*

A GPS network extending 100 km across the San Andreas fault system from Point Reyes to the Great Valley has been repeatedly measured since 1990. Relative positions were obtained with the Bernese version 3.2 software and solutions use orbits improved with data from a global scale fiducial network. Average station velocities between 1990 and 1993 show 32 ± 2 mm/yr of fault-parallel (N33°W) shear distributed across the profile (Figure 3). We find negligible shear near the Great Valley. The fault-normal (N57°E) component of displacement shows no significant motion or shape. The total rate of displacement across this profile is less than the 39±2 mm/yr velocity of the Sierra Nevada microplate relative to the Pacific plate rate estimated from VLBI measurements.

![Figure 3. Plot of observed and predicted rates of N33°W velocities. Error bars are ±1 sd. Vertical lines indicate the locations of the San Andreas, Rodgers Creek and Green Valley faults. See text and Table 1 for descriptions of the various models.](image)

We model a spatially dense sampling of the deformation obtained by combining the results from the North Bay GPS profile with Geodolite trilateration and VLBI data. Assuming that deformation is constant in time and that the San Andreas, Rodgers Creek, and Green Valley are responsible for the deformation we estimate the slip rates that best account for the observed deformation. The use a simple 2D model where the faults are represented by one or more infinitely long parallel vertical cuts in an elastic half space. Results are summarized in Figure 3 and Table 2. Model 1 is a forward model using geologic estimates of slip rates on the faults. This model fits the geodetic data.
II

best in the center of the deformation field but is discrepant at the southwestern and northeastern points. Model 2 is a least squares inversion for the slip rates on the faults. In Model 3 is a variation of Model 2 where we assume block motion across the Green Valley fault. In Model 4 we assume that slip is distributed uniformly at depth from the San Andreas fault to the Green Valley fault and allow shallow creep on the Green Valley fault. The distributed shear zone in Model 4 is essentially the sum of \( n \) discrete faults in the limit as \( n \) approaches infinity and the slip on each approaches zero. Model 2 provides the best fit to the data. All of the models predict between 38 and 40 mm/yr of slip on the San Andreas fault system consistent with the motion estimated by VLBI.

Table 2. North Bay 2-D Fault Models

<table>
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<tr>
<th>Fault</th>
<th>Depth km</th>
<th>Model 1 mm/yr</th>
<th>Model 2 mm/yr</th>
<th>Model 3 mm/yr</th>
<th>Model 4 mm/yr</th>
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<tr>
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<td>12 - inf</td>
<td>19.0 ± 4.0</td>
<td>14.8 ± 1.3</td>
<td>14.3 ± 1.3</td>
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<tr>
<td>Rodgers Creek</td>
<td>10 - inf</td>
<td>9.0 ± 2.0</td>
<td>11.5 ± 1.8</td>
<td>14.8 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>Green Valley - Deep</td>
<td>10 - inf</td>
<td>9.0 ± 3.0</td>
<td>12.9 ± 5.4</td>
<td>6.9 ± 1.3 *</td>
<td></td>
</tr>
<tr>
<td>Green Valley - Creep</td>
<td>0 - 3</td>
<td>4.0 ± 2.0</td>
<td>2.7 ± 2.8</td>
<td></td>
<td>10.5 ± 5.6</td>
</tr>
<tr>
<td>Shear Zone</td>
<td>10 - inf</td>
<td></td>
<td></td>
<td></td>
<td>31.4 ± 1.3</td>
</tr>
</tbody>
</table>

* For the Block Model, the Green Valley fault has a depth of 0 - infinity.

12. Systematic Difference Observed between Geodolite and GPS Measurements of Line Length

![Figure 4. Difference between Geodolite and GPS measurement of line lengths as a function of line length. Error bars are ±1 sd. Statistics for linear fits are shown in inset.](image)

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Comparison of 76 line lengths show Geodolite measurements are on average 0.4 ppm long relative to GPS (Figure 4). Before comparing the line lengths we corrected the Geodolite measurements by -0.14 ppm to account for the difference in assumed values for the velocity of light. Geodolite, GPS, and steel tape measurements of two 18 m baselines are consistent at the ±1 mm level. The difference between Geodolite and GPS increases with line length suggesting a scale dependent error. Refractivity corrections for Geodolite rangings are obtained from profiles of temperature and humidity flown with a light aircraft combined with measurements of air pressure taken at the ground stations. A possible source for systematic error is the correction we apply to the measured temperature for frictional heating of the temperature sensor exposed to a fast airflow. This correction varies with the square of the airspeed and has a value of \( \sim 1^\circ C \) (or 1 ppm) at the typical airspeed of 100 knots. Determining the source of the observed systematic difference between the measurement systems is important primarily for extending the record of deformation in the future with GPS. A scale correction to all Geodolite measured lines lengths will not produce any change in the previously determined rates of strain.

**Reports Published in FY 1993 (excluding abstracts)**


Earthquake-Potential Evaluation of the Oquirrh Fault Zone, Central Wasatch Front Utah

Award No. 1434-92-G-2218
Program Element II
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INTRODUCTION

The Oquirrh fault zone extends along the base of the Oquirrh Mountains on the east side of Tooele Valley in the eastern Great Basin (figure 1). This fault zone has long been recognized as a potential source for large-magnitude earthquakes that would affect the city of Tooele, Tooele Army Depot, Dugway Proving Ground, and population centers along the nearby Wasatch Front.

The purpose of this study is to characterize the timing and size of prehistoric surface-rupturing earthquakes on the fault zone through a program of aerial photograph interpretation, scarp profiling, detailed logging of trenches excavated across the fault zone at two sites, and radiocarbon dating of material from key stratigraphic units in the trenches to constrain the timing of prehistoric surface-rupturing earthquakes.

INVESTIGATION RESULTS
(April 15, 1992 through October 1, 1993)

Scarps of the Oquirrh fault zone offset the Provo shoreline of Lake Bonneville (Bonneville lake cycle, 32-10 kya; Provo shoreline 14.5-14.2 kya [Machette and others, 1992]) and previous studies of scarp morphology (Barnhard, 1988; Barnhard and Dodge, 1988) suggested that the most recent surface-rupturing earthquake occurred between 9,000 and 13,000 years ago. Results of this investigation show that the most recent surface rupturing earthquake on the Oquirrh fault zone is younger than previously suspected and provide information on the size and timing of the penultimate event.

Big Canyon Trench Site

The Utah Geological Survey excavated three trenches across the Oquirrh fault zone near Big Canyon in 1992 (figure 1). Two of the trenches exposed evidence for a post-Lake Bonneville surface-rupturing earthquake.
rupturing earthquake. Bulk samples collected from an organic-rich debris flow directly beneath the colluvial wedge yielded approximate mean residence time (AMRT) radiocarbon age estimates of 6,840±100 14C yr B.P. and 7,650±90 14C yr B.P. An AMRT radiocarbon age estimate of 4,340±60 14C yr B.P. on a bulk sample from an unfaulted, organic-rich debris-flow deposit exposed in the third trench provides a minimum-limiting age for the event. Based on those dates, the most recent surface-rupturing earthquake on the Oquirrh fault zone occurred sometime within an approximate 3,400 14C-year interval between about 7,700 and 4,300 14C years ago, making the event significantly younger than previously suspected.

Pole Canyon Trench Site

A single trench was excavated at Pole Canyon (figure 1). It exposed direct evidence for two surface-rupturing earthquakes and indirect evidence for a third. Stratigraphic relations in the trench show that the most recent event is younger than the Bonneville lake cycle (as demonstrated at Big Canyon) and that the penultimate earthquake is older than the transgression of Lake Bonneville across the site (elevation approximately 4,750 feet). Charcoal from a lake-related marsh deposit directly overlying the penultimate-event colluvial wedge gave a radiocarbon age estimate of 20,370±120 14C yr B.P., and establishes a minimum-limiting age for the penultimate event. (All radiocarbon age estimates at Pole Canyon were obtained using an atomic mass spectrometer). Several flecks of disseminated charcoal from a fine-grained stream deposit displaced by the penultimate event yielded an age estimate of 26,200±220 14C yr B.P., establishing a maximum-limiting age for the earthquake. The penultimate event on the Oquirrh fault zone occurred sometime in an approximate 5,800 14C-year interval between about 20,400 and 26,200 14C years ago. A second radiocarbon age estimate of 33,950±1,160 14C yr B.P. was obtained from a single fleck of detrital charcoal from the fine-grained stream deposit indicating that the charcoal in the deposit spans a considerable age range.

A buried fault scarp (eroded free face) and associated slope colluvium on the upthrown side of the fault predate the penultimate event and provide indirect evidence for a third surface-rupturing earthquake. The fault and associated colluvial wedge for this third event are concealed below the bottom of the trench. Timing of this earthquake is unknown, but it predates both Lake Bonneville and the penultimate event.

Recurrence Interval and Net Slip

Using the time constraints determined for the most recent (4,300 to 7,700 14C years) and penultimate (20,400 to 26,200 14C years) events, the average recurrence interval for surface-rupturing earthquakes on the Oquirrh fault zone ranges between about 12,700 and 21,900 years. This recurrence interval is based on the two most recent events on the fault zone and may or may
not reflect the long-term behavior of the fault.

The regressive Bonneville shoreline is present on both sides of the fault zone in the Pole Canyon trench. The shoreline was displaced 2.5-3.0 meters (net slip) down to the west during the most recent event; an unexpectedly large amount considering the mapped length (10 km) of surface rupture. A vertical displacement of that size is normally associated with earthquakes of magnitude 7 or greater.

REPORTS

The following brief reports and abstracts presenting preliminary results of the Oquirrh fault zone earthquake hazard evaluation have been prepared:


REFERENCES


Figure 1. Location of the Big Canyon (BC) and Pole Canyon (PC) trench sites on the Oquirrh fault zone, Tooele County, Utah (after Barnhard, 1988).
TEMPORAL AND SPATIAL BEHAVIOR OF LATE QUATERNARY FAULTING, WESTERN UNITED STATES
AND
MAP OF MAJOR ACTIVE FAULTS OF THE WESTERN HEMISPHERE

9950-10215

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PURPOSE OF PROJECT

This project consists of two discrete but interrelated tasks that are combined for administrative reasons. In 1993, the bulk of activity and NEHRP funds were directed to the “World Map of Major Active Faults, Western Hemisphere”, which is co-sponsored by the International Lithosphere Program (ILP). The common theme for both tasks is to define regional variations in the time-space distribution of late Quaternary paleoseismic activity as a guide to understanding the accumulation and release of strain on active faults and folds and to improve the quality of geologic input to seismic hazards analyses. Project members are Michael N. Machette, Richard L. Dart, and Kathleen M. Haller.

INVESTIGATIONS

1. The ILP sponsored map project will compile World, Continental, and United States maps of major active faults in support of their new Global Seismic Hazards Assessment Program (GSHAP). This work began in earnest in mid-1992 with a carefully chosen list of participants for the Western Hemisphere. We are still enlisting technical experts from Canada, the United States, and Mexico/Central America that are known to be both productive and knowledgeable, and which have strong national contacts. For the United States, the compilation will be supervised by the USGS in Denver, under the direction of this project. In addition, the USGS will assist compilers in the other regions with digitization and technical aspects of the data base.

Our strategy is to assemble a large body of data on Quaternary faults and folds in the U.S. Although many authors have compiled maps, few have taken the time to fully document their maps with supporting databases; thus, fault data in catalog form is relatively sparse. Overall, we suspect that there is existing catalog data for about 20% of the faults and folds in the U.S.

The customers for these products include internal (USGS) and external NEHRP scientists, as well as scientists, engineers, planners with state and local governments, universities, and consulting firms. We are using ARC/INFO on a SUN workstation for the map preparation and are compiling a relational database (FoxPro, Microsoft Corp.) of fault and fold data on Macintosh computers. However because most of the intended users do not have Macintosh computers, we also intend to distribute the data in DOS and/or Windows versions of the database. CD-ROM versions will come with a run-time version of the program and digital map files to for easy access at low user cost.

2. Machette, Haller, and Kelvin Berryman (visiting scientist from New Zealand Geological Survey) completed the description, mapping, and sampling of six large exploratory trenches that were excavated in Pleasant Valley, south of Winnemucca, Nevada in 1992. Four of the trenches were placed across surface ruptures of the 1915 Pleasant Valley earthquake (estimated Richter magnitude 7.3/4) in order to investigate the timing of prehistoric faulting. Two additional trenches were located on nearby pre-1915 fault scarps: one on a valleyward strand of the Tobin Scarp and a second that is to the north along the frontal fault of the Sonoma Range in Grass Valley. Samples for thermolumines-
cence dating (at The University of Ohio) were submitted in the spring of 1993, and results should be available in the spring of 1994. Results of this trenching study are being prepared for a U.S. Geological Survey-sponsored Redbook Conference on Paleoseismology in September 1994 (organized by Yeats, Schwartz, and Prentice).

3. Crone and Machette published two comprehensive manuscripts (USGS Bulletins) that describe the results of their 1991 Gilbert Fellowship field studies of the 1988 earthquakes at Tennant Creek, Australia (Crone and others, 1992) and Marryat Creek, Australia (Machette and others, 1993). In addition, they prepared several abstracts and a paper that summarize their work. These manuscripts discuss the implications of long-recurrence intervals for intraplate faulting. In addition, they continued dating studies using thermoluminescence (cooperatives with J. Hutton and J. Prescott, University of Adelaide, and H. Millard, USGS) and electron-spin resonance (cooperative with K. Tanaka, CRIEPI, Tokyo, Japan) to better define the minimum time for the penultimate faulting events and for stratigraphic control on rates of deposition.

RESULTS

1. During FY 93, we conducted a number to planning and progress meetings for the active fault map portion of the project. These are described briefly as follows:

   South America: ILP meeting Feb. 11-14, 1993 in Quito, Ecuador. National representatives from Argentina (H. Basitas, S.A. Coordinator), Chile (R. Thiele), Columbia (J. Romero), Ecuador (H. Yepes and A. Eguez), Peru (J. Machare), and Venezuela (C. Giraldo) presented plans for completing a preliminary draft of their respective maps by August 1994. Commitments for Bolivia and western Brazil are still lacking.

   Central America: Commitments have been obtained for compilation of San Salvador and Guatemala (G. Dengo), Honduras (M. Gordon), Panama (P. Mann), and Costa Rica (W. Montero); although little actual compilation has occurred to date.

   Caribbean: A coordinating meeting was held at AGU in San Francisco on Dec. 7, 1993, to further formulate plans for this region. We currently hold commitments for Puerto Rico (B. McCann), Hispanola (P. Mann and C. Prentice), and part of Cuba (M. Gordon). Further commitments should be made in late 1993. We discussed plans with P. Mann and M. Gordon to hold a special session at the 1994 AGU meeting on Active Faulting in the Caribbean.

   Mexico: Our first Mexico meeting was held in conjunction with the International Conference on Exotic Terranes in Guanajuato on Nov. 12, 1993. F. Ortega (national representative) invited about 25 scientists to participate and about 20 of these attended. Although no responsibilities were assigned, Ortega will select 6-8 scientists to lead the compilation in specific regions. There appears to be a high-level of interest and commitment to this project from the Mexican scientific community. A draft map of Mexico might be completed in about a year, and a progress meeting will probably occur at one of their national earth science meetings in the fall of 1994.

   United States: We conducted project business at two meetings this year. At the GSA meeting in Reno in May, we had an opportunity to discuss the status of compilation for most of the western states, and to gain further commitments. At AGU in San Francisco, we held our first meeting concerning the California map of active faults, and were partially successful in gaining commitments. The main problems with California are the large number of faults and folds and the overwhelming amount of data that must be compiled.

By the end of FY 93, we had obtained digital data for Quaternary faults in California, Nevada, Utah, Colorado, the west half of Montana, and parts of New Mexico. The California faults were scanned in Menlo Park using a specially prepared version of Jennings’ 1992 fault map. This file has been edited, but needs to be revised to reflect changes made on the upcoming (1994) version of Jennings’ map. In addition, there is concern of the part of the CDMG about release of digital data. The USGS
and CDMG are currently discussing how and when such data can be released. The files for most
other states come from sources within the USGS or from state geological surveys which do not hold
copyrights to their products (Table 1).

In May, we released a comprehensive list of guidelines for the compilation of the digital map and
database. This report includes definition of terms, examples from compiled faults, extensive notes
for the data comment fields, and sample forms. The guidelines have been distributed widely, and
are being used by many of those listed in Table 1.

We have been testing our methods of digitization and data compilation on an area of western Montana and eastern Idaho, where we had previous experience with Quaternary faulting. The results of
this pilot study were presented at the GSA meeting in Reno, and we received many favorable
comments. The product is nearly complete, and we intend to submit the map and text data for USGS
review in early 1994. In addition, a preliminary version of the California and Nevada fault maps
were presented at the AGU meeting in San Francisco. The response to these poster sessions
indicates a high demand for the digital products.

<table>
<thead>
<tr>
<th>State/region</th>
<th>Map and Type</th>
<th>Database and Type</th>
<th>Main Contacts</th>
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<td>A. Text, unpublished</td>
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<td>B. Partial, text; ca. 1987</td>
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<td>Talwani, Prowell, Tuttle (?)</td>
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<td>(offshore), 1992</td>
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<td>Walsh</td>
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TABLE 1. Status of Quaternary fault data for selected regions of the United States
[Data quality: A, good; B, adequate; C, poor or nonexistent]
2. Preliminary interpretation of results from our Pleasant Valley trenching study were presented at GSA in Reno. Our early interpretation emphasized long recurrence intervals and no evidence of Holocene faulting had been found. However, preliminary identification of an ash found in the Sheep Creek trench suggested a probable correlation with a 1-2 ka eruption in the Mono Craters area (A.M. Sarna-Wojcicki). This new data forced us to interpret the penultimate faulting event as late Holocene, a conclusion that seemed unlikely from geologic and geomorphic considerations. Further field studies at several sites along the Pearce scarp revealed no geologic evidence for a late Holocene faulting event. Also, further examination of the ash by Sarna-Wojcicki showed only 3% tephra in the sample; thus, the sample cannot be correlated with any source with confidence. Final interpretation of results are pending the completion of thermoluminescence dating of 10 samples from a number of the trench sites. Preliminary dates suggest that an interpretation of long average recurrence intervals (tens of thousands of years) is correct.

3. The results from our Gilbert Fellowship research on intraplate faulting in Australia (see reports listed below) show that historic intraplate earthquakes typically reactivate ancient faults, but are characterized by long recurrence intervals. On September 29th of 1993 another historic surface-rupturing earthquake was added to the international catalog, bring the total to 11 events. The Latur, Southern India earthquake only had a magnitude of 6.3 (Ms), but it proved to be devastating—causing more than 10,000 deaths, and hundreds of thousands of injuries. The earthquake reportedly had at least 1 km (and possibly as much as 3 km) of rupture, which places it well above the lower threshold for rupture events in intraplate regions. In Australia, the 1970 Calingiri (Ms 5.7) and 1986 Marryat Creek (Ms 5.8) earthquakes caused 3 and 13 km of surface rupture (respectively), whereas the Tennant Creek sequence (Ms 6.3-6.7) formed three scarps with 34 km of surface rupture.

REPORTS


Investigations undertaken:

The San Bernardino, California, area lies across the northern portion of the seismically active San Jacinto fault zone and is bounded to the north by the San Andreas fault zone. We obtained high quality hypocenters to investigate the seismic characteristics of the San Jacinto and San Andreas fault zones to identify seismological and geological features which may bound individual fault segments, which will help estimate the probable extent of fault rupture in individual earthquakes.

Sanders [1989] proposed a tentative segmentation model of the northern San Jacinto fault zone based on fault geometry observed at the surface (here we use his segment names). We can examine the seismicity patterns along and between each segment to determine if the surface fault geometries extend to seismogenic depths. A throughgoing fault that connects the aligned San Bernardino strand of the San Andreas fault zone and the Coachella Valley segment of the Banning fault can be hypothesized. Here we use microseismicity patterns to test for the presence or absence of a throughgoing fault.

To get high quality hypocenters we invert 560000 arrival times of 23000 earthquakes in a 1° by 2° area surrounding San Bernardino, California for hypocenters and 3-D P-wave velocity structure.

Results:

The boundary between the Lytle Creek-Glen Helen and San Bernardino segments is marked by a 3 km right step in the surface trace of the faults that is also defined by the hypocenters (Fig. 1, cross section BB'). This boundary is the location of a sharp 5 km step (shallower to the north) in the maximum depth of hypocenters (cross section AA').

At the surface the boundary between the San Bernardino and San Jacinto Valley segments is a 2 km left step between the fault traces. This step is not seen in the hypocenters (cross section CC'). Hypocenter depths gradually shallow southward by 2 km across the boundary. This boundary is also the site of the intersection of the Banning-Crafton Hills fault zones. The San Jacinto Valley segment lacks shallow (<8 km depth) earthquakes that are common along the San Bernardino segment (cross section AA').

The San Jacinto Valley segment has relatively few earthquakes but its location and near vertical attitude can be defined with hypocenters (cross section DD'). This segment is on strike with the hypocenter lineation defining the Anza segment (cross section EE'). Earthquakes are deeper on the Anza segment. In cross section FF' the hypocenters define a slight right bend as the Anza segment bends to the more northerly strike of the San Jacinto Valley segment. It appears that the large right step between the San Jacinto Valley and Casa Loma segments (occupied by San Jacinto Valley) does not exist at depth. The south end of
the Hot Springs segment is well defined by hypocenters. An east dipping hypocenter plane connects the Anza and Hot Springs segments (cross section FF').

The hypocenters image two features along the San Andreas fault zone in the study area. One is an abrupt 6 km shallowing of the maximum depth of earthquakes going from south to north. The other is the north dipping Banning fault zone (including the Garnet Hill fault and Crafton Hills fault zone). In places the two features are coincident.

In the east part of the study area the step in maximum hypocenter depth is vertical to steeply southwest dipping and its position appears to be controlled by the Mission Creek fault (cross sections GG', HH' and II'). Further west the step changes attitude to north dipping (cross sections JJ', KK', and LL') and it appears to be the down dip continuation of the Banning fault zone until it intersects the San Jacinto fault zone.

The Banning fault is best expressed in the seismicity pattern as aftershocks of the North Palm Springs earthquake (cross sections GG' and HH'). The depth extent of these aftershocks appear to be controlled by the tread or riser of the depth step. Further west the north dipping Banning fault zone is defined by the hypocenters in cross sections II', KK', and LL' until the Banning fault zone intersects the San Jacinto fault zone.

Two of the three examined segment boundaries along the northern San Jacinto fault zone do not appear as significant at seismogenic depths as they do at the surface. The Anza segment appears to connect directly with the San Jacinto Valley segment which in turn appears to connect directly to the San Bernardino segment. This is notable in light of the identification of the Anza segment as a slip gap where future earthquakes may originate.

Near the San Andreas fault zone the step in maximum hypocenter depth reflects fundamental differences in rock properties between each side of the step. We interpret the step as a result of juxtaposition of different rock types by large scale displacement along the San Andreas fault zone. The presence of the step may have controlled the location of the western part of the Banning fault zone as it formed. The step may be offset by the San Jacinto fault zone. The depth step between the Lytle Creek-Glen Helen and San Bernardino segments of the San Jacinto fault zone (cross section AA') is similar in character to the step in maximum hypocenter depth along the San Andreas fault zone. The offset between the depth steps is 20 to 25 km, comparable to the total offset along the San Jacinto fault zone (24 km). This may support the idea that San Andreas slip is transferred to the San Jacinto fault zone via the Banning fault.

The step in maximum hypocenter depth along the San Andreas fault zone strikes obliquely to a hypothetical throughgoing fault that connects the aligned San Bernardino strand of the San Andreas fault zone and the Coachella Valley segment of the Banning fault. The depth step crosses such a fault without any apparent offset. We conclude there is not such a throughgoing San Andreas fault in the study area.

Reference:

Report published:
Figure 1. Relocated earthquakes and cross section locations. Heavy line indicates location of the step in maximum depth of earthquakes along the San Andreas fault zone. Symbol size scales to earthquake magnitude.
Figure 1, continued. Cross sections near the San Jacinto fault zone. Cross section AA' indicates some of the segment names used.
Figure 1, continued. Cross sections near the San Andreas fault zone. Note the step in maximum depth of earthquakes.
A Friction-Feedback Model for Seismicity at Parkfield, California

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ABSTRACT. Between mid-1989 and mid-1991, the San Andreas fault at Parkfield, California, experienced a major change in the number and size of microearthquakes taking place there. Parts of this activity are organized into a migrating earthquake sequence with a propagation speed much slower than possible in models of fault interactions based on simple elasticity and frictional sliding. Instead, this sequence can be modeled by a coupled, 2 layer, block-slider system governed by interacting velocity-weakening and velocity-strengthening frictional forces. The coupling between the two layers is assumed to be viscoelastic, accounting for aseismic slip on ductile portions of the fault. To represent the Parkfield asperity, a set of blocks in the velocity-weakening layer were given greater frictional resistance. This friction-feedback model shows how the asperity forms a barrier to a migrating sequence and how one aspect of plate motion redistributes its slip along a weak fault zone.

REPORT. The San Andreas fault at Parkfield, California, continues to be an important focus of the US program in earthquake prediction (1; Figure 1). In fact, over the past year or so this area has experienced a notable increase in earthquake activity, including m=4.7 and m=4.8 events that triggered public earthquake warnings (2). In this paper, using microearthquake data we have collected at Parkfield (3, 4), we demonstrate that a significant, episodic, change in microearthquake activity occurred several years prior to these events. We also provide a simple "friction-feedback" model for the observed space-time pattern of the microearthquakes. These patterns show rates and distances of earthquake migration that can not be explained in terms of redistribution of fault slip by elastic loading of asperities held together by simple friction. Instead, the seismicity suggests an interactive process of seismic and aseismic slip within and below the seismogenic portion of the fault.

A time- and distance-dependent sum of earthquake numbers, magnitudes, and moments can be used to demonstrate the existence of the migrating earthquake sequence (5, 6). Such a sum can be visualized from a latitude verses origin-time plot of the microearthquake data in Figure 1 (as we show and discuss later in Figure 4). By taking strips of data oriented in different ways on such a plot, and summing, for example, the number of event within a given strip, a
moving increase or decrease in activity can be detected. For equal weighting of each orientation, or migration velocity, the areas of the strips must be kept constant. This is so that in the case of a homogeneous space-time distribution of microearthquakes, the sums of numbers, magnitudes, and moments are also constants, independent of migration velocity.

The results of this analysis for Parkfield microearthquakes are shown in Figure 2. In this plot, cumulative number, magnitudes, and moments are displayed as functions of migration velocity and arrival time at latitude 36°59.5', which is the latitude of Middle Mountain (Fig. 1). Migration velocities representing changes traveling both from the north and south were include in the analysis, with the center of the velocity axis representing a 100 day wide strip moving at infinite velocity. The cumulative numbers of events, magnitudes, and moments have been contoured to show the regions of significant changes. Examples of such changes are the earthquakes and aftershocks that have occurred since late 1992, which show up as regions of tightly spaced contours of high values moving at large velocities. The specific feature we focus on here is an increase in microearthquake numbers that arrived at Middle Mountain in the last half of 1990 and traveled from the north with a velocity between 21 and 78 km/yr (Fig. 2). Because the earthquakes in this event were all very small, it did not result in significant increases in cumulative magnitude and moments.

We have studied the statistical significance of the features seen in Figure 2 using a jack-knife approach to finding the standard deviation of the values shown (7, 8). At the time of the 1990 southward-migrating seismicity increase, the maximum number of events in the analysis strips was at least 180 ± 13, as compared to a before and after background of 100 ± 10 or so. Thus the number of migrating earthquakes during this episode was on the order of 7 to 8 times the jackknife error of our analysis. The of this event being random can also be crudely estimated by noting that it is the only one of its kind in our data. Partitioning the velocity-date diagram into cells the size of the 1990 event (0.5 yr long and traveling N-S, S-N, or at infinite velocity), it seems that this type of event could occur randomly at most 1 time in 40 or so.

We propose that the migrating earthquake sequences at Parkfield are due to the interaction of brittle and ductile failure, in large part near the base of the mostly brittle, or seismogenic zone (9-11). The model we propose assumes a weak San Andreas fault that is strongest near this base, below which the fault is mostly ductile and weakens relatively slowly with further depth, as illustrated in Figure 3a. Both the brittle and ductile zones are subject to the strike-slip forces of plate motion, with failure of both zones tending to occur near their boundary, where this system is the strongest. At Parkfield this picture is supported by the fact that the largest microearthquakes with the largest stress drops tend to occur at this depth (4, 12).

To show how this model accounts for the migrating earthquake sequences, we have reduced it to a system of simple block-sliders, shown schematically in Figures 3b and 3c (13-15). The model consists of two, coupled, one-dimensional layers of spring-connected block-sliders with different frictional properties. In this representation, after being loaded to failure, the upper layer of blocks resists
sliding with a velocity-weakening friction law. In the lower layer, the frictional resistance is assumed to increasing with the velocity of the blocks. The blocks of each layer are coupled together by a system of dashpot-spring units (Maxwell bodies). The dashpot-spring units represents the viscoelastic character of the two crustal layers, accounting not only for their elastic connection, but their relaxation properties as well.

The specific system of blocks for our Parkfield model consists of 100 blocks: 50 brittle and 50 ductile, numbered from south to north. One end of the 2 layer system was assumed to represent the creeping San Andreas fault north of Middle Mountain. The steady pull of the lithospheric plates was applied to the ductile layer at this end. The southern end of the system was assumed to extend south of the Gold Hill area. The static friction of the entire system was randomly varied by a maximum of 10%. To account for the presumably stronger, aseismic Parkfield "asperity" near Middle Mountain where the previous M=6 earthquakes nucleated (16), the static friction of brittle blocks 15 to 22 was increased by an average of 60%.

The equations of motion in non-dimensional form were derived from Lagrange's equation. These were numerically integrated for many thousands of time steps and hundreds of cases of relative strength, stiffness, relaxation time, and velocity weakening and hardening rates (15). Failure and rapid slip of the blocks in the brittle layer were identified as microearthquake events, whose total area and slip were used to calculate relative magnitudes. The location and size of the events were then displayed in the same fashion as the latitude-magnitude-origin time plot of the Parkfield events, as shown in Figure 4. In the case shown in Figure 4b., the dashpot-spring unit had a relaxation time of 0.5 time units and an instantaneous stiffness approximately an order of magnitude larger than that of the 2 layers.

The main feature of our block-slider simulation of Parkfield seismicity is the appearance of event sequences with migration speeds below simple brittle redistribution of the plate slip. The differing speeds result from the damped feedback between the frictional properties of the brittle and ductile layers. Evidently, parts of this 2 layer, friction-feedback system can hang up, producing a period of low activity followed by a slow, southward migrating seismicity front. Rapidly moving fronts also appear, in both the north and south directions, as in recent Parkfield seismicity. The different migration speeds are a consequence of slip-energy snaking back and forth between the brittle and ductile layers.

The blocks that model the Parkfield asperity form a barrier to the southward migrating sequences: events either terminate or propagate northward from there. Presumably a simultaneous failure of the asperity blocks would represent a repeat of the Parkfield earthquake. Some activity does take place within the asperity and to its south, as slip in the ductile zone passes it by. Either the strength of the brittle zone is too high or the load too slow and small. Moreover, both the system of block-slider and method for calculating event size have natural limits that may not cover this case.
References and Notes.

2. J. Langbein et al., ibid 74, 152-153 (1993); the second warning was issued by the USGS Parkfield Working Group, Menlo Park, J. Langbein, Chief Scientist, after the m=4.8 on November 14, 1993.
4. P. E. Malin et al., ibid 244, 557. (1989).
5. This general approach was suggested to us in various stages by, T. McEvilly, A.J. Michael (e.g., A.J. Michael, EOS 74, 43, 447, 1993), and one of our past reviewers. Its implementation here is our own.
6. The moments and corner frequencies were determined from the S-wave frequency spectra using the methods of D. J. Andrews, in Earthquake Source Mechanics, K. Aki and P. Richards, Eds., American Geophysical Union Monograph 37, American Geophysical Union, Washington, D.C., (1986). The largest earthquake in 1990 was a local magnitude 3.3; the m=4.7 took place on Oct 20, 1992, rupturing a few kilometers of fault and producing a more typical aftershock sequence (2).
8. The estimates of the statistical errors in velocity-time analysis were found by 3 jackknife studies of the data. For the 3 tests, the data were randomly assigned to one of 15, then 30, and finally 60 different groups. Jackknife errors were then calculated for each set of groups.
17. We thank colleagues at the University of California at Berkeley and the United States Geological Survey for sharing the effort of keeping the Parkfield downhole seismology project alive. This work was support by DOI-USGS grant #14-08-0001- G1375.

Figure Captions.

Fig. 1. Part (a). Map of the seismicity along the San Andreas fault at Parkfield, California. The downhole seismic stations used in this study are shown as triangles, the Middle Mountain station at MM and the Gold Hill station at GH. Part (b). Cross section along the San Andreas fault at Parkfield, California, showing the hypocenters of the microearthquake in the study time period. A total of 2,700 events are show in both plots.

Fig. 2. A migration velocity verses arrival time analysis of the Parkfield microearthquake data shown in Fig. 1. The velocity are for events coming from both the north and south and the arrival time is that at Middle Mountain. The effects of aftershocks have been supressed by removing days with more than 4 nearby earthquakes. Three analysis are shown: (a) cumulative number of earthquakes, (b) cumulative magnitudes, and (c) cumulative moments. The larger earthquakes and their aftershocks are visible on the right, in late 1992 and 1993. The N-S migrating increase in numbers of earthquakes discussed here arrived at Middle Mountain in the last half of 1990, moving southward at roughly 36 km/yr.

Fig. 3. Part (a). A hypothetical strength verses depth curve for the San Andreas fault at Parkfield. The curve is based in part on numerous events and higher stress drops near the bottom of the seismogenic zone (4, 9). Below this level the fault begins to weaken at a relatively slow rate. Part (b). The velocity weakening and velocity hardening friction laws assumed for the brittle and ductile layers of the model (10, 12). Part (c). A schematic representation of the brittle and ductile layers at Parkfield in terms of a block-slider system of springs, dashpots, and masses.

Fig. 4. Part (a). Earthquake magnitudes along the San Andreas fault as a function of latitude and time. The magnitudes of the events are represented by circles of different sizes, with the October M=4.7 earthquake being the largest and M~0 the smallest. Arrows point out the proposed slow (#2) and rapid earthquake migration sequences (#1, #3, #4). Part (b). Results of the friction-feedback model of Parkfield seismicity. As in Part (a), the sizes of the ellipses represent the relative sizes of the events. As indicated by the arrows, both slow, regional and rapid, local earthquake sequences can be simulated with this type of model.
a) 12
N-S 36
velocity km/yr 78
12

b) 12
N-S 36
velocity km/yr 78

Arrival time at Middle Mountain 509
(a) TIME MAGNITUDE PLOT

Minutes North of 35 Degrees

Box 1

Box 2

Box 3

Box 4

Time (mo.yr)

(b) FAULT SIMULATION

NORTH

SOUTH

TIME UNITS

511
Arrival at Middle Mountain
Instrumentation to Improve the Washington Regional Seismograph Network
1434-92-G-2195  S.D. Malone and R.S. Crosson, P.I.s

Program Element II.2

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Introduction

This contract is for the purchase and installation of four new, high quality broad-band digital seismograph stations as an addition to the Washington Regional Seismograph Network (WRSN). It also includes funding for the development of the data acquisition process and integration of these data into the routine data collection and analysis procedures. In addition to the four stations supported under this contract, a prototype station (LON), situated on the same pier as the DWWSSN station at Longmire WA (near Mount Rainier), has been operating for the entire contract period. By the end of the contract period, there will be a total of 7 high quality seismograph stations operating in the Pacific Northwest (5 operated by the WRSN, one by USNSN; NEW and one by IRIS-USGS; COR).

Progress

During this contract period, we completed installation of three new broad-band three-component stations. Two of these (LTY at Liberty, WA and SSW at Satsop, WA) time-stamp, digitize, and record data on-site. Data of interest are periodically retrieved from each site to the UW over phone lines. Station SSW has the highest dynamic range, since it has 24 bits/sample as compared to 16 bits/sample at LTY and LON. We are evaluating recordings from these instruments to determine how to optimize the recovery of useful data. The third station, near Tolt, Washington (TTW), also uses a 3-component broadband sensor and digitizes andtime-stamps data on-site, but all of the digital data is continuously telemetered to the UW Seismology Lab by radio and recorded there. Eventually, the data from this site will be reformatted into USNSN format and transmitted to the National Seismic Network in Golden, CO via satellite. Station TTW is currently being operated in a test mode. Figure 1 shows the current network configuration. Table 1 gives the locations of the installed broad-band stations. Selection of an additional broad-band site near Port Townsend in Puget Sound is still pending.

Using an adaptation of the IRIS GOPHER dial-up system, we are routinely recovering broad-band data from Liberty, Satsop, and Longmire (LON) and archiving it with our short-period network data. We are working towards closer integration of the two data types. One of our students, Gia Khazaradze, has developed a technique to generate synthetic Wood-Anderson records from the broad-band data. This will allow us to determine local magnitudes from the broad-band data.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>WRSN 3-component Broadband Stations Operating as of 9/30/93</th>
</tr>
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<tbody>
<tr>
<td>STA</td>
<td>LAT</td>
</tr>
<tr>
<td>LON</td>
<td>46 45 00.0</td>
</tr>
<tr>
<td>LTY</td>
<td>47 15 21.2</td>
</tr>
<tr>
<td>SSW</td>
<td>46 58 20.4</td>
</tr>
<tr>
<td>TTW</td>
<td>47 41 40.7</td>
</tr>
</tbody>
</table>

513
In the previous contract period, we developed and tested a SEED writer for trace data from our analog telemetry network. Because all of the analog data is digitized and time-stamped simultaneously, header information is minimized. During this contract period, we expanded the SEED writer to incorporate data from both broad band and short-period stations. The broadband data, digitized and time stamped at each individual station, is combined with data from our analog stations (digitized and time stamped at the UW) to form a single SEED file. These SEED files will eventually be stored at the IRIS Data Management Center where they will be easily available.

We have completed all hardware requirements for installation of the VSAT communications link from Seattle to the USNSN; through which we plan to receive data from the USNSN station at Newport, WA (NEW) and possibly other stations. NEW is a high-quality, low-noise site and is the only station in Washington east of 118° N longitude. It provided valuable short-period information to the WRSN via telephone lines for many years until the phone line to the UW was terminated in 1987 (data is now telemetered to the NEIC).
Figure 1: Stations either operating at the end of the third quarter, 1993, or installed early in the fourth quarter. Broad-band stations are shown as larger shaded triangles. Short-period station RCM was installed at Camp Muir on Mt. Rainier 3rd quarter. New short-period stations in southern Oregon installed in October are HAM (Hamaker Mt.), LAB (Little Aspen Butte), VSP (Spencer Mt.), and VRC (Rainbow Creek).
GEOMENSOR MEASUREMENTS IN THE IMPERIAL VALLEY MEKOMETER NETWORK, 1993

1434-93-0-2299
Program Element II.3
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Investigation

In 1991, we initiated a program for leveling our network, starting with the central block of stations, which we extended northwards to provide better coverage of the Imperial fault and the Brawley seismic zone north of their junction. The principal objective of the 1993 fieldwork was to make a trilateration survey of the 1991 extension, with a suitable overlap of the main block. We also planned to tie in a small number of NGS benchmarks used by IGPP, La Jolla, in a 1991 kinematic GPS survey of the network, and to re-measure such lines on and around the fault as time permitted.

Results

The fieldwork, started early in March, was completed by early May. It involved the construction of 18 stations to strengthen the otherwise weak (for trilateration surveys) northern part of the network, and the measurement of 432 lengths, involving 345 lines (Figure 1). About half the lines measured were lines first leveled in 1991, but not previously connected horizontally. The remainder were on and around the Imperial fault, intended to assess movements since the last complete trilateration survey, in 1987. We also tied in four NGS benchmarks that had been occupied repeatedly by GPS during recent years. The standard error of the measurements was about 1 ppm.

It was not part of the 1993 plan to do any leveling. However, we did re-level a 9 km length of the most northerly east-west line (Keystone Road), first leveled in 1991. We also measured vertical angles to all new stations, to enable slope lengths to be reduced to horizontal.

Preliminary analysis of 14 fault-crossing lines spanning a 12 km length of the Imperial fault south of Ferguson Road indicated a mean creep of about 70 mm between the Springs of 1987 and 1993. This compares with a predicted 57 mm based on measurements made up to 1987, the 13 mm excess being approximately equal to the creep induced on the fault by the November 1987 Superstition Hills earthquake sequence.

Re-leveling of the Keystone Road line, which spans the Mesquite basin and includes the Imperial fault and the Brawley seismic zone, revealed a sag of about 20 mm across the basin between 1991 and 1993, but no significant changes associated with either the fault or the seismic zone.

Following completion of our work, IGPP conducted a kinematic GPS survey of the network which will make use of the present measurements and the 1991 leveling data.
Figure 1. Lines measured in 1993. Solid circles are original stations connected previously in three dimensions, open circles are stations built and leveled in 1991 but not previously connected horizontally, crosses are new stations.
Investigations

This research project addresses the problem of how the Cascadia subduction margin of the Pacific Northwest responds tectonically to varying convergence angles and rates with the objective of understanding whether the timing, style, and rates of regional tectonic deformation can be attributed to plate kinematics. This problem can be approached both spatially and temporally in the Pacific Northwest as active convergence directions and rates vary along the margin. Current research utilizes the technique of forward modeling to reconstruct plate geometries and kinematics in the Pacific Northwest and the technique of geohistory modeling to discern the record of tectonism in late Cenozoic rocks and sediments along the southern Washington margin, along with more traditional geologic techniques to quantify rates of fault movement and tilting of strata.

Although current seismicity is low along the Cascadia margin, geodetic monitoring of interseismic strain accumulation reveals coupling between the Juan de Fuca plate and North American margin, and the Holocene paleoseismic record in the Pacific Northwest reveals cycles of widespread abrupt subsidence of coastal marshes attributed to release of interseismic strain accumulation. Upper Cenozoic rocks and sediments in this region also record a history of intense and episodic tectonism that reflects convergence between the Juan de Fuca and North American plates. Field investigations in coastal Washington have identified several sites with geomorphic and stratigraphic evidence of youthful folding, faulting, uplift or subsidence. Strata at these sites are being examined in detail to quantify recent tectonic deformation.

Field investigations during FY93 included reconnaissance of tilted and faulted Quaternary deposits at a new site and establishment of benchmarks for monitoring fault activity and active diapirism at two other sites.

Lab investigations during FY93 included microscope analysis of microfossils collected from Quinault Formation and tephra analysis of tuffaceous clasts from faulted Quaternary deposits from another site.
Results

1. Quaternary sand and gravel deposits overlying the Neogene Quinault Formation display minor folding with fold axes trending east-west and a fold wavelength of 2 to 5 km. These folds are superimposed on a major regional fold with an east-west trending synclinal axis near the Queets River. At certain sites along the southern Washington coast this general pattern of crustal shortening is interrupted by zones of more intense deformation. In particular, a number of sites with highly tilted or faulted sediments have been identified. Some fault zones, active during the Miocene, continue to transport fluids (diapirism) and in one area several reverse faults appear to break the soil surface. This regional deformation pattern suggests that the abrupt subsidence events recorded in marsh strata may reflect regional shortening due to crustal structures activated either during megathrust events or perhaps separate from megathrust events. This hypothesis is being addressed in southern Washington by this project (and in Oregon by other workers) by documenting young vertical movement (inelastic strain) along the coastline with the aim of determining whether the entire coastline subsides during seismic events or instead the coastline undergoes shortening with the intermarsh areas rising while marshes subside.

2. Established benchmarks at two of the diapir/shear zones that appear most active in order to quantify rates of vertical movement and address the hypothesis that these features may act as strain meters.

3. Continued investigation of highly tilted and reverse-faulted Quaternary strata adjacent to a diapir with the aim of determining whether this local crustal structure is seismogenic and whether paleoliquifaction features documented along the Copalis River ca. 11 ka can be attributed to a local seismic event.

4. Continued analyses of sedimentary rock samples collected in southern Washington in FY89 and FY91 for age and uplift data. Rock samples collected in FY92 have been processed for microfossil analyses.

Reports


BAY AREA DIGITAL SEISMIC NETWORK

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Award 14-08-0001-G2122; Element II.7

Goals

The purpose of the Hayward Fault Network (HFN) in the San Francisco East Bay is to provide high resolution, high frequency (1000 samples per second), wide dynamic range (24-bit digitization), 3-component, on-scale seismic data for earthquakes of magnitude 0 < M < 7.0 for detailed studies of the Hayward fault. From our experience managing the Parkfield High-Resolution Network, with similar dimensions to the HFN, we believe we can accomplish this goal even in a noisy urban environment, given carefully designed sensors and deep borehole emplacement.

The HFN is a joint effort with the USGS. The network as envisioned will consist ultimately of 24-30 stations, 12-15 each north and south of the San Leandro seismic gap, managed respectively by UCB and USGS. Other sites are being drilled by the State of California Transportation Department (CALTRANS) and instrumented by the Lawrence Livermore National Laboratory (LLNL) at the major Bay Area bridges. Sensors designed and constructed at UCB/LBL are being installed in the entire network. Recording and telemetry equipment will differ between north and south, but the resulting data will be shared in near real time and archived with CALNET data in common format in the Bay Area optical mass store facility at Berkeley, also operated jointly by UCB and the USGS, and will thus be made promptly available to the research community.

FY 93 Accomplishments

During the past fiscal year we have installed and operated a network of four borehole seismometers on the northern Hayward fault. As a temporary system, RefTek Model 72-A07 24-bit event recorders borrowed from the UCB Seismographic Station and Lawrence Berkeley Laboratory operate independently at each site, recording on DAT tape. The central-site acquisition and control workstation (SPARCstation 10) was delivered and installed, and successfully reads the DAT tapes from the field recorders. The permanent Quanterra recorders and communication software are on order and a prototype system is undergoing bench testing at Berkeley.

1. Sensor Installation and Data Collection.

Six-component borehole sondes, with three channels of acceleration and three of velocity, have been emplaced in four holes of opportunity at depths of up to 600 feet along the northern Hayward fault. Identical downhole sensor packages were provided to Malcolm Johnston of the USGS for colocation in dilatometer boreholes on the southern Hayward fault, and to Larry Hutchings at LLNL for installation in boreholes drilled by CALTRANS at three piers of the Dumbarton bridge. Site information is specified in Table 1.

We have experienced some problems with sonde leakage at the cablehead, resulting in a mid-course design change. In addition, noise spikes cause occasional false triggers, apparently due to induced voltage steps on the long cables carrying the low-level signals. Subsequent units will amplify the signals in the sonde if this problem cannot be reduced sufficiently by careful grounding.

We hope to install sensor packages in several more holes of opportunity in the coming year in cooperative efforts with CALTRANS, EPRI, LLNL and the California Division of Mines and Geology.

It should be noted that the BRffi borehole, drilled by the USGS, is multi-use: The UCB/HFN sensor package presently shares the borehole with a USGS dilatometer. These will eventually be joined by a broadband seismometer operated by the UCB Seismographic Station as part of the Berkeley Digital Seismic Network (BDSN). Continuous geodetic GPS measurements, begun in the fall of 1993, are archived by the Seismographic Station.

2. Central Site and Field Data Loggers.

The SPARCstation10, to be the central data acquisition and control platform, has been operational for a year. The Quanterra field recorders, once installed, will communicate with the Sparc10 computer over 38 kb ADN phone lines. There will then be central event detection and other network controlling decision-making.

At Berkeley, Quanterra Company and UCB personnel recently installed for in-house bench-testing the prototype acquisition software and central-to-site communication handshaking on a conventional Quanterra field data logger simulating those to be deployed on the network. Necessary software modifications were identified. We expect
delivery of the final Quanterra data loggers during early 1994, with fully functional operation of the complete system by the end of the year.

3. Data
Earthquakes have been recorded on the array now for about one year with the temporary 24-bit event recorders. Many of the local earthquakes are located within an interesting cluster of events beneath Berkeley; others are elsewhere along the Hayward fault. We are evaluating noise reduction and bandwidth achieved with respect to surface sites, compared to similar borehole installations in non-urban areas (e.g., Parkfield, Anza, The Geysers, Long Valley). The slowly growing data base will be placed on the regional mass store system at Berkeley. The increased time resolution, dynamic range and bandwidth attained will be useful in refining our definition of crustal structure in the East Bay region, in delineating the spatial-temporal complexity of the clustered events along the fault, in our investigations of earthquake source dynamics, and in developing localized elements of the real-time earthquake warning systems presently under development using the northern California broadband network.

<table>
<thead>
<tr>
<th>Table 1. Hayward Fault Network Station Information</th>
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<td>Site</td>
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<td>Northern sites (UCB):</td>
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<td>Southern sites (USGS)</td>
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<td>Dumbarton Bridge (LLNL/CALTRANS)</td>
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<td>PIER44</td>
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Notes:
- Latitude and longitude are with respect to 1927 North American Datum (NAD27).
- Elevations are with respect to mean sea level.
- Elevations and depths are with respect to local ground level at the well head.
- Locations of UCB sites were obtained by GPS measurements, accurate to ±1m or better.
- Locations of USGS and LLNL sites are preliminary, from 7.5' topographic maps.
- UCB site BRIB is colocated with USGS dilatometer site RRCS.
- The east and west ends of the Dumbarton Bridge are equipped with sensors at three depths. The deepest instrument at all three sites is 100 feet into bedrock.
Figure 1. Hayward Fault Digital Network.
INTRODUCTION

Two programs of seismic wave analysis continue: Earthquake recording with the high-resolution seismic network (HRSN), begun in December, 1986, and controlled-source monitoring with HRSN begun in June, 1987.

The HRSN (Figure 1) consists of ten, 3-component, borehole seismometers surrounding the 1966 Parkfield epicenter. The data-acquisition system features digital telemetry with 125-Hz bandwidth and 16-bit resolution, and can operate in external-trigger (i.e., controlled-source) or event-trigger (earthquake) modes. Low-gain recorders with similar parameters, on loan from the IRIS PASSCAL instrument pool, are operating at five of the sites in parallel with the telemetry system. Network characteristics are summarized in Karageorgi et al., 1992.

In a related effort (non-NEHRP funding), the UC Berkeley Seismographic Station has established a broadband seismometer at Parkfield called PKD1. The seismometer is presently in a temporary installation, and will be moved to a permanent site in the first half of 1994. This site is now an integral part of the Berkeley digital network, and data from it have contributed to a paper on real-time magnitude estimates (R. Uhrhammer) being readied for submission.

INVESTIGATIONS

1) Microearthquakes.

Local microearthquakes of magnitude about -0.5 to about +1.8 are routinely recorded on scale by the high-gain, telemetered system, extended to near M5 at the five low-gain sites. A 3-D velocity model (Michelini and McEvilly, 1991), a high-precision relative hypocenter location procedure for clustered events with similar waveforms, and other tools have been developed for high-resolution analyses of local earthquakes. Clustered events are being studied for evidence of temporal changes in fault zone processes and properties, including anisotropy. Studies are underway in source scaling, failure processes, fault zone structure, and material properties within the Parkfield nucleation zone.

2) Controlled-source monitoring with HRSN.

From June, 1987 through December, 1993, the HRSN has been illuminated 47 times with S-waves of three polarizations at seven source positions throughout the study zone, using a shear-wave Vibroseis source, in an ongoing, long-term monitoring program (Figure 1). The resulting data are searched for temporal variations of wave propagation characteristics throughout the nucleation zone. Data reduction is accomplished at the Center for Computational Seismology (CCS) in the Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL). This work was reported by Karageorgi, et al., 1992.

DATA COLLECTED

Considerable progress has been made (R.N.) to put the 1987-1993 microearthquake data base into a consistent and correct format. Problems with channel assignments, amplitudes, time code interpretation, data gaps, and format are being dealt with. The final results are to be placed on the Berkeley regional mass-store by the end of 1994. A total of approximately 4000 events are presently in the archive.

Four vibrator data sets have been collected and the data reduced in this project year. Data after routine processing (edit, stack, correlation, gather by source site) are archived in SEGY format on magnetic tape.

RESULTS

Earthquake Studies:

Event analysis: Local Parkfield events are now picked and located with the 3-D model within a month of occurrence. This effort is presently current through December, 1993.
Characterization, Redefinition, and Preliminary Analysis of Similar Event Clustering, 1987-1992 (R.N): Using a modification of the similar event characterization method of Aster and Scott, 1993, we have characterized event similarity for the 1987-92 Parkfield HRSN data set, and reformulated our definition of similar event clusters at Parkfield based on three characteristics: 1) a bimodal distribution of correlation coefficients, defining clustered and unclustered events - see Figure 2, 2) cluster size stability, and 3) visual inspection of waveforms. Results are shown in Figure 3. The spatial, temporal, and relative size characteristics of the clustered and unclustered seismicity yield important information about fault zone dynamics during the earthquake nucleation process.

Preliminary results suggest:

1) Clustering is much more extensive at Parkfield than was previously believed, accounting for about 2/3 of all recorded events.

2) Clustering is concentrated at depths of less than 5km and on the creeping section of the fault NW of Middle Mountain.

3) Spatial distribution of clusters correlates with features of the velocity model of Michelini and McEvilly.

4) There is a bimodal distribution of correlation coefficients which we believe relates to a physical dichotomy in source processes and proximity.

5) Clusters can be unambiguously defined in terms of the bimodal correlation distribution.

6) The maximum characteristic cluster dimension is approximately 400 m.

7) A bimodal recurrence interval distribution suggesting two physical clustering processes, one of which imitates the lognormal behavior used in earthquake forecasting.

8) Clusters often contain events having magnitudes differing by over two orders.

9) The standard deviation of recurrence intervals within individual clusters seems to correlate with the range of magnitudes.

10) The existence of a characteristic recurrence interval for clusters.

11) That the characteristic recurrence interval is experiencing a temporally varying trend.

Fault-Zone Modeling (WF): We have carried out a detailed analysis and interpretation of the 3D $V_p$, $V_s$, and $V_p/V_s$ models of the San Andreas fault (SAF) zone at Parkfield first presented by Michelini and McEvilly (1991). The main feature of the $V_p$ model is a deep high-velocity anomaly (Figure 4) that corresponds to the locked patch detected by Harris and Segall (1987) and to the 1966 rupture plane. This feature is similar to, but smaller than the high-velocity body (HVB) detected in our $V_p$ model of the Loma Prieta segment of the fault zone at the opposite (NW) end of the central creeping section of the SAF. We proposed (Foxall et al., 1993) that the fault plane within the high-velocity body at Loma Prieta slips unstably (stick-slip) and acts as the barrier to stable fault slip at that end of the creeping section. Concentration of stress at the barrier under continuing tectonic loading causes it to evolve to the asperity which failed as the 1989 Loma Prieta earthquake. We propose that the same mechanics apply to the HVB at Parkfield: The HVB acts as the barrier that arrests slip at the SE end of the creeping section, and evolves to the asperity that fails during Parkfield earthquakes.

The main feature of the $V_p/V_s$ model is an intense positive anomaly immediately NW of the HVB (Fig. 4). The amplitudes of the $V_s$ and $V_p/V_s$ anomalies indicate that this is a dilatant, saturated damage zone caused by the intense stress concentration in front of the barrier. Equivalently, this dilatant volume can be interpreted as the process zone at the crack tip of a stably propagating, -150 km long megafracture corresponding to the central creeping section of the SAF. The 3-4 km length of the $V_p/V_s$ anomaly provides an upper bound on the length of the process zone, and is consistent with published estimates of -0.5-2.5 km for the lengths of process zones associated with earthquake nucleation. Figure 4 shows that this dilatant zone is presently aseismic. According to the hypocenter locations computed by Ellsworth et al. (1994), the 1966 foreshock and mainshock nucleated within the process zone in front of the barrier, although the mainshock hypocenter is located below the most intense $V_p/V_s$ anomaly.

The coincidence of the $V_p/V_s$ anomaly with the nucleation zone of the Parkfield earthquakes under Middle Mountain has important implications with regard to weak fault zone models that have recently been proposed. In one class of these models (Byerlee, 1993; Sleep and Blanpied, 1992) high fluid pressure is maintained within a sealed fault zone during the interevent interval by shear-related compaction. Therefore, the first characteristic that distinguishes the Parkfield nucleation zone (and perhaps other nucleation zones) is that it is dilatant rather than compacted during the interevent interval. The saturated condition of the zone indicates that it exists under drained...
conditions and is recharged from the surroundings at a rate comparable to the dilation rate. This implies that if the fault zone is sealed elsewhere, then the seals (lateral, vertical or both) must be broken at the nucleation zone. If recharge is through lateral hydraulic conductivity with the country rock, then this would suggest that the fluid pressure within the dilatant zone is low relative to the proposed overpressured fault zone elsewhere. In this case, the high $V_p/V_S$ zone is undergoing dilatant hardening, consistent with nucleation of the Parkfield earthquakes there, the relatively low rate of interevent microseismicity within the zone, and the high stress drops that characterize events that occur in this vicinity (O'Neill, 1983).

Source Scaling (PJ): The earthquake sequences of October 1992 and November 1993, which produced the only two A-level alerts in the history of the Parkfield project, have provided a rich data set for investigating the scaling of earthquakes in the range M -0.7 to M 4.7, about 5 orders of magnitude. Earlier work involving spectral ratios of larger events to smaller events suggests that earthquakes with magnitudes in the range 0.5 to 1.0 have corner frequencies of about 100 Hz, near the upper end of our bandwidth (125 Hz).

We have been investigating the utility of a very simple technique for estimating source properties also. Following O'Neil and Healy (1973) and Frankel and Kanamori (1983), we computed rupture duration from the initial pulse widths (time from onset to the first zero crossing) on velocity recordings of Parkfield earthquakes. For several dozen earthquakes, we have measured pulse widths at five sites.

The study is complicated by the contrast in attenuation between the two sides of the San Andreas fault. The pulse widths show a clear path dependence, with sites to the southwest of the fault (where Salinian granite dominates the ray path) indicating rupture times which average roughly half those of sites at similar distances to the northeast, where waveform attenuation through a large thickness of Franciscan formation decreases the bandwidth. Pulse width decreases with moment and at the northeast sites appears to level off at the lower magnitudes.

To the southwest of the fault, the VCA station, for example, records waveforms whose rupture times as derived from the pulse widths continue to decrease linearly with magnitude, from a value of 0.040 s to 0.015 s over the magnitude range 4.7 to 0.2, the smallest earthquake studied for this site to date (moment = 3 x 10e18 dyne-cm). No bottoming out of pulse widths is observed over this magnitude range at this station.

The inferred rupture times for events recorded at VCA correspond to corner frequencies lower than those estimated from spectral ratios. We are now in the process of trying to separate the effects of attenuation and source processes.

Controlled-Source Studies (EK):

The final working data sets for analysis are "time gathers": one source into one receiver gathered across calendar time, producing 720 files, each containing, at present, 47 similar traces on most paths. The time gathers are then examined for variations in waveform parameters.

Most displays show only seasonal variations in various properties (travel time, amplitude, spectral properties). Seasonal variations are due to very near-surface moisture changes under the vibrator (Clymer and McEvilly, 1981).

However, paths in the vicinity of source site 2, south-west of the 1966 epicenter, show a prominent travel-time anomaly that began in mid 1988, and continues at least through October, 1992 (Figure 5). No significant change was found in the anomaly with special surveys run during the October, 1992 M4.7 sequence. But 1993 data show an apparent reversal of the anomaly for late arrivals on paths 2-MMN and 2-VCA. Note that these measurements were also made after an exceptionally rainy winter following several years of drought, raising the possibility that the anomaly was due to the drought. Measurements along 2-RMN continue to show the anomaly, and 2-SMN continues to show no significant variations. There is some indication of a return of the anomaly on 2-MMN and 2-VCA in mid-November, 1993. Continuing measurements will help to distinguish seasonal variations from any on-going long-term anomaly.

Present efforts are focused on the determination of the depth of penetration of the waves showing the anomaly, and verification of the anomaly using repeating, clustered microearthquakes as the sources of seismic waves.

References


Byerlee, J, 1993, Model for episodic flow of high-pressure water in fault zones before earthquakes, Geology, 21, 303-306.


**Publications:**


**Ph. D. Theses:**


Foxall, W., Fault-Zone Heterogeneous Slip and Rupture Models of the San Andreas Fault Zone Based upon Three-Dimensional Earthquake Tomography, 1992.

**Papers Presented on Parkfield Research in 1993.**

1993 Fall AGU, San Francisco:


Figure 1. Location map showing the Parkfield borehole seismometer network, vibrator positions, and microearthquake seismicity for 1987-1992 (about 1700 events).

Figure 2. Event pair similarity (beta) vs. hypocenter separation (offset) in percent of events compared at each offset. Of special interest is the sudden rise in similarity at offsets less than 400-500 meters indicating a dramatic change in earthquake source processes at these near offsets. This discontinuous behavior is used as the basis for an unambiguous definition of clustering at Parkfield.
Figure 3. Cross-section with 1987-1992 seismicity along the San Andreas fault. Horizontal (y) axis shows distance from the epicenter of the 1966 Parkfield earthquake. Circles show the centroid location of clusters; dots show unclustered events. Locations of recording sites of the HRSN are shown as projected onto the fault plane.

Figure 4. Along-strike section through the Parkfield Vp/Vs model showing the positive Vp/Vs anomaly centered at y=-1 km and z=-7 km, under Middle Mountain (y=0.0). Outline of the high-velocity body from the Vp model is superimposed (heavy line). Locations of the 1966 mainshock and foreshock are shown as filled circle and square, respectively.
Figure 5. Travel-time variations relative to a reference trace (arbitrarily chosen, here in mid 1988) measured across the repeated 16-sec seismograms in a moving window for several paths from vibrator site two.
Program Element: II.1

Geologic and Tectonic Framework, Mendocino Triple Junction
9540-70420
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Investigations:

(1) The primary objective of this project has been to produce a colored digital geologic data base for the Mendocino Triple Junction (MTJ) region. At the time of the Petrolia earthquake in April, 1992, a geologic mapping study of the region had been completed and the geology was compiled onto a greenline base at 1:100,000 scale. We proposed to digitize this data base in ARC-INFO and make it available in a timely manner for use in various anticipated geophysical and geodetic investigations. The digital compilation was begun in January 1993.

(2) At the invitation of K.R. Aalto (Humboldt State University) McLaughlin spent four days with him in the Cape Mendocino area, mapping and sampling a previously inaccessible part of the coast between False Cape and Bear River. Aalto had found some complexly deformed rocks there which were assigned to the Eocene Coastal terrane of the Franciscan complex. We suspected them to be a much younger, exhumed part of the offshore Cascadian accretionary complex.

Results:

(1) Digital compilation of the Cape Mendocino and Eureka 1° x 1/2° quadrangles was undertaken at the outset of calendar year 1993 in anticipation of the focus of post-Petrolia earthquake investigations. We especially wanted these maps to be useable for a planned deep seismic reflection and refraction study scheduled for 1993 and 1994 calendar years. In addition, a bathymetric base was added from offshore U.S. Coast and Geodetic Survey data, and structural data from the offshore work of D.H. McCulloch and S.H. Clarke, Jr., were also added to the map. Preliminary full-color digital geologic maps were presented at a GSA Cordilleran section meeting poster session in April, 1993. An interpretive text, including rock descriptions, paleontologic data, major onshore and offshore faults, structure sections, and a tectonic synthesis were prepared, and the maps were routed into...
technical review late December 1993. Following the review process, we plan to release the maps to open file in CD-ROM, or in a similar rapid-release format, after their submittal to BWTR. Work on the Garberville 1:100,000 digital map begins in calendar year 1994.

(2) Mapping in the False Cape part of the MTJ region and micro-paleontologic data (diatoms, foraminifers, radiolarians) confirmed the presence of a part of the early Miocene Cascadian accretionary margin onshore north of Cape Mendocino. These rocks are exhumed from beneath the Eocene Coastal terrane of the Franciscan Complex along out-of-sequence thrusts, and are folded through the older accretionary complex, possibly in response to coupling between the Gorda and North American plates. These early Miocene deformed rocks were named the False Cape terrane and are assigned to the Franciscan Complex. The distribution of these rocks, to the extent known was added to the Cape Mendocino-Eureka map base.

Reports published:


Report submitted to Branch Review, 12/93:

McLaughlin, R.J., Ellen, S.D., Aalto, K.R., and Carver, G.A., with contributions to offshore geology by S.H. Clarke, Jr., in review, 1993, Geology of the Cape Mendocino and Eureka 1:100,000 quadrangles, northern California: 2 map plates, scale 1:100,000 descriptive and interpretive text, 49 manuscript pages and 2 structure sections (plate 3).
Loma Prieta Data Archive Project

1434-92-G-2228
Program Element II.1
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Introduction

Under the general editorship of the U.S. Geological Survey (USGS), the National Earthquake Hazards Reduction Program (NEHRP) is issuing the official report to Congress describing the post-earthquake investigation of the October 17, 1989, Loma Prieta, California earthquake. That report will synthesize results of earthquake research funded and performed by a wide range of investigators. These investigators have produced or gathered a variety of data sets generated by the earthquake or produced as a result of research into the earthquake. Of necessity, the NEHRP report will not be a suitable medium for distributing this extensive data.

The nonprint data is extremely important to organize and preserve since it will not be published in the open literature and, unless preserved, will be lost to future scholarship. The Loma Prieta earthquake is the first major earthquake in the San Francisco Bay Area since 1906 and is the first to occur in a high populated, heavily instrumented area. The data will form an important baseline for research into future earthquakes in this area and elsewhere.

The National Information Service for Earthquake Engineering (NISEE) at the Earthquake Engineering Research Center (EERC) was charged by the National Science Foundation in 1971 to gather and disseminate information in earthquake studies particularly earthquake engineering. As a result of the Loma Prieta earthquake, NISEE founded the National Clearinghouse for Loma Prieta Earthquake Information in 1990. The clearinghouse has gathered data from a wide variety of sources and published the Loma Prieta Clearinghouse Catalogs, listing more than 2100 sources of information on or about the earthquake.
Investigations Undertaken

NISEE has established the Loma Prieta data Archive to gather, organize, and issue the raw data associated with the Loma Prieta earthquake in one coherent format. In particular, NISEE will

* identify the data sources produced as a result of the earthquake
* gather them together
* organize and issue the data on CD-ROM with a printed users’ guide
* deposit the guide and CD-ROMs in selected national and university libraries throughout the country as well as distribute them at cost to anyone interested
* publicize and disseminate the archive to researchers worldwide

The data from the Loma Prieta earthquake is extremely important to preserve since this earthquake occurred in a heavily populated area where there were a great number of strong-motion instruments. There is more data available for study from this earthquake than for any significant earthquake in recent history. Therefore, experimental data will be used as a baseline for future research in the Bay Area and other locations. In addition, making this data generally available will allow for independent verification of results by other researchers.

Results Obtained

About 25 data sets have been obtained and about 25 more will be acquired. They range from seismological to engineering to social science data sets and include digital files, survey responses, text, videos and slides. These have been processed and copied to computer files where they are being stored til the completion of the project.

Reports Published

The U.S. Geological Survey (USGS) Professional Paper series which will constitute the NEHRP Report to Congress will be completed some time in 1995. At that time, the data sets will be written to CD-ROM. A printed guide to the data will be issued as an addendum to the Professional Paper series. The CD-ROMs themselves will be distributed by NISEE at cost.
ANNUAL REPORT
SOUTHERN CALIFORNIA EARTHQUAKE PROJECT
93-9902-11010

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INVESTIGATIONS

This project encompasses the USGS personnel that work together on the Southern California Seismic Network to ensure that earthquakes are well-recorded and archived in southern California, and that reliable seismic information is communicated to government agencies, scientific groups, media, and the public. The routine analyses and archiving of data involves close cooperation with Caltech and the Southern California Earthquake Center (SCEC). With the recent emphasis on providing rapid information, the project provides the necessary coordination of developing automated computer systems and organizing people that quickly respond to significant earthquakes. The project also includes the scientists' individual research topics that are closely tied to seismic data collected by the network. Tasks for FY1993 were divided into 3 categories.

- Seismic Data Collection
- Earthquake Hazards Monitoring and Public Information
- Earthquake Research

Seismic Data Collection
(Elements II.2, II.7, III.1, IV.1)

A major responsibility of the project is to maintain and operate the large seismic network, thus a substantial part of the project's resources are used for instrument maintenance. The network consists of over 300 channels of data from 225 sites and provides the primary data for hazard monitoring in southern California and data for much of the research done by the project scientists. Responsibilities for hardware (instrument sites, radio telemetry, microwave and telephone links, computer cluster) and software (on-line recording system, off-line data processing, real-time earthquake information systems) are shared jointly with Caltech.

In addition to maintaining the network, we continue to try and improve our seismic recording capabilities by installing new sites in sparsely instrumented areas, adding Force-Balance-
Accelerometers (FBA) to improve on-scale recordings of larger earthquakes, and installing broadband TERRAscope instruments with large dynamic range. FBA components and the TERRAscope data are crucial for both the development of better real-time information systems and the on-going research of seismic waveforms.

Routine analysis of the data is also carried out cooperatively with Caltech and includes, interactive timing of phases, location of hypocenters, calculation of magnitudes and preparation of the final catalog. Phase data are stored on magnetic disks and waveform data are archived on an optical mass storage device operated by the SCEC Data Center. These data are readily available to other USGS and university users over INTERNET connections.

Earthquake Hazard Monitoring and Public Information
(Elements II.1, IV.2)

An important part of monitoring earthquakes in a populated region such as southern California, is the ability for scientists to have access to quick and accurate locations and magnitudes. This enables them to release timely information to government officials and the media following felt and damaging earthquakes. Also, real-time locations and magnitudes are useful for watching large aftershock sequences and providing possible information on forthcoming activity. Our current systems have performed fairly well during the numerous felt events over the past year and scientists have been able to quickly announce hypocentral information to government agencies and the media. To further increase our response capabilities, we are working to improve the reliability and speed of applications to improve the automated event locations and magnitudes. In addition to hypocenters and magnitudes of the earthquakes, we are developing further real-time utilizations such as, alarms for unusual activity in special study areas, designation of likely areas of damage from future large earthquakes, and rapid assessment of earthquake probabilities.

Earthquake Research

Project scientists pursue a diverse range of seismological research topics which contribute to studies of the earthquake Source (I), Potential (II), and Effects (III). Many of these studies utilize the large database of seismicity and waveforms that is collected and archived by the seismic network.

Earthquake Rupture Processes (Elements I.2, III.2) D. Wald, Heaton

We are developing the methodology to study the relationship between long-period source models of large earthquakes and those determined from higher frequency data. This relationship is critical for understanding faulting dynamics as well as for the prediction of ground motions in the higher frequency range of engineering interest, particularly where strong motion data is absent. Using a joint inversion of long-period (including geodetic) and short-period waveform data, we are investigating the rupture process of large, strike-slip earthquakes using a finite fault modeling techniques.
Foreshock and Aftershock Statistics (Elements II.2, II.8) Jones
Based on the statistical properties of foreshock and aftershock distributions, short-term probabilities of future large events can be estimated from any earthquake occurrence, as possible foreshock or expected aftershocks. A computer program has been developed to evaluate and display the probability of damaging earthquake shaking (> 10%g) for the next 24 hours based on the long term estimates from geologic information modified by the probability that recent earthquakes recorded by the Network are foreshocks or will have aftershocks.

Source Parameters of Small Earthquakes (Element II.2) Mori
We continue to study source parameters (moment, stress drop, energy, fault planes) from small earthquakes (M 3.5 to 4.5) which are well recorded by low-gain components of the network. Previous work has shown that using a smaller event as an empirical Green function, one can successfully remove complicated site and path effect from short-period waveforms so that we can make reliable estimates of source properties.

Three-Dimensional Crustal Structures (Elements I.1, II.5) Eberhart-Phillips
We are working on a 3-D Vp and Vp/Vs model for the Landers region. The current study focuses on velocity variations along the Landers mainshock rupture primarily using the data set from the 100-km 3-component array deployed by the USGS from Barstow southeastward along the Landers rupture and to the San Andreas fault. We are examining velocity variations along the rupture to discern whether the correlation between high-velocity and high slip and the correlation between large velocity gradients and nucleation, that have been found along the San Andreas, can also be applied to this fault which has less cumulative slip and may even involve some freshly fractured sections.

Teleseismic Network Waveform Studies (Element II.4) L. Wald, Heaton, Mori
We have been using surface waves and body wave from teleseisms recorded on over 500 stations of the southern and northern California arrays to study velocity structures of the Earth. The surface wave data consisted of 10 to 20 sec Rayleigh waves that travel complicated paths across California. We have tried to identify the anomalies that are complicating the surface wave propagation by tracing their paths across the arrays. We are also studying body waves, such as the core reflection PcP, to determine velocity structures of the Earth's deep interior.

RESULTS

Seismic Data Collection
This Project (in cooperation with Caltech) provided the basic information for seismicity in southern California. Data collection during FY1993 included locating and archiving over 23,000 earthquakes, with the activity dominated by the continuing aftershocks from the M7.3 Landers and M6.2 Big Bear earthquakes of June 28, 1992. Weekly reports on the seismic activity were sent out to over 40 government and university groups. Annual summaries of the seismicity and network operations are published in the 1992 (L. Wald et al., 1993) and 1993 (in preparation) Network Bulletins. Some specific improvements to the data collection effort that were accomplished during FY1993 are listed below.
- Data accessibility has improved with preliminary earthquake locations and magnitudes available to USGS and university researchers within a few minutes following an event. Hand-timed phase data are available within 24 to 48 hours. Using INTERNET connections to the SCEC Data Center, waveform data are now usually available within a week. There is currently over 230 Gbytes of waveform data available to users on the SCEC mass storage device.

- Portable instrument data collected by USGS instruments (47 Reftek recorders and 5 continuous 5-Day recorders) following Landers have been played back and organized. Procedures have been developed to associate this data and the other portable data collected by various universities with the network data.

- The Superstition Hills TERRA scope site became operational in August 1993.

- A GPS (Global Positioning System) survey was carried for most of the network stations to determine their locations within 10 m.

- FBA's were installed at 2 sites to improve on-scale recordings of larger earthquakes and horizontal components were installed at 3 sites to improve recording of S waves for hypocenter depth control.

Earthquake Hazard Monitoring and Public Information

Project personnel responded to numerous felt earthquakes throughout the year, ensuring uninterrupted data recording and providing information to local government agencies and the media immediately following the events. Listed below are some of the earthquake responses and improvements to the information systems that were made during FY1993.

- There is a new Earthquake Information Hotline which gives current seismic activity in southern California, 818-395-3100.

- We made significant improvements to the software systems which automatically determine and broadcast earthquake locations and magnitudes. The intense activity during the Landers-Big Bear sequence emphasized some of limitations of the Real Time Processor (RTP) we have relied on in the past. So during the past year we have developed and have operational a new set of programs called ISAIAH (Information from a Seismic Array In A Hurry). The new system analyzes all 300 channels of data (the RTP used only 64 channels) and has an improved phase associator that can better distinguish multiple events that occur closely spaced in time.

- Portable seismic instruments were deployed in the epicentral areas of the M5.3 Cataract Creek, Arizona earthquake of April 29 and the M6.0 Eureka Valley, California earthquake of May 17.

- Project scientists gave over 75 talks and presentations to various civic, professional, and educational groups to communicate the importance of understanding earthquake hazards in southern California.

Earthquake Research

Most of the research results for the year focused on the Landers-Big Bear earthquake activity. General summaries have been written and co-authored by project scientists (Jones et al., 1993,
Sieh et al., 1993, Mori et al., 1992, Hauksson et al., 1993). Results from four of the specialized areas of research also contributed new information about this sequence.

- **Earthquake Rupture Processes**
  Studies of the Landers earthquake (Wald and Heaton, 1994) from the simultaneous inversion of strong-motion, teleseismic and geodetic data resolved important details of the slip function, including the timing delays as the rupture jumped from one fault segment to the next (Fig 1). These results can be also displayed graphically with color animation of the rupture front and the radiated energy.

- **Foreshock and Aftershock Statistics**
  A detailed study was completed of the foreshock-mainshock-aftershock probabilities of Joshua Tree-Landers-Big Bear sequence (Jones, 1994). This paper also examined the probabilities of activity may trigger a large San Andreas earthquake (Fig 2). This work forms the basis for a plan by California Office of Emergency Services to issue an Imminent Earthquake Alert in response to possible foreshocks on the San Andreas.

- **Source Parameters of Small Earthquakes**
  Details of the rupture nucleation for the Landers earthquake were studied using near-field records (Abercrombie and Mori, 1994). This study clarified the locations and sizes of the smaller (M4-5) preliminary subevents of the Landers rupture. Another paper (in preparation) estimates source parameters, such as the slip area, rupture directivity and stress drop for the M4.3 Joshua Tree foreshock.

- **Three-Dimensional Crustal Structures in the Landers Area**
  The 3-D velocity structure along the Landers rupture zone showed that the region north of the Johnson Valley fault zone has the most velocity heterogeneity while along the Landers and Homestead Valley fault segments, the velocity is relatively uniform. At the juncture of the Homestead Valley and Emerson fault segments, where the bend in the seismicity trend is best defined, there is a pronounced high-velocity body east of the fault rupture (marked by arrow in Fig 3). 20-km northwest of the high-velocity body, the volume between the Camp Rock and Calico faults is characterized by low-velocity and appears graben-like. The seismicity does not extend through this low-velocity region.

Progress was made on other research topics including, developments in solving for Vp/Vs in three-dimensional velocity inversions (Eberhart-Phillips), source studies of the 1923 Kanto earthquake (D. Wald), large array analyses of body and surface waves from teleseisms, and 3-D gravity model of the Los Angeles Basin (Eberhart-Phillips).
Figure 1. Time window contributions to the final slip model of the Landers earthquake. The contour interval is 0.5 m.
II, III, IV

Pre-Landers Probability that M6 is foreshock

- Probability that M6 is foreshock if $P(C) = 5\%/yr$
- Probability that M6 is foreshock if $P(C) = 1.3\%/yr$
- Probability of M6 aftershock

Days since the Landers Earthquake

Figure 2. The characteristic foreshock probability for M6 event in the Palm Springs region assuming a long-term probability of 5%/yr (top) and 1.3%/yr (middle). Bottom curve is the probability of an M6 or greater Landers aftershock occurring within 10 km of the San Andreas fault in the Palm Springs region.

Figure 3. P-wave velocities along the east side of the Landers rupture. Arrow marks the high velocity body at the juncture of the Homestead Valley and Emerson faults.
REPORTS

Articles that Received Director’s Approval in FY1993


**Articles In Press or Published during FY1993.**


Experimental Tilt and Strain Instrumentation

9960-12126

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Program Element II

Investigations

1. There are currently 160 Data Collection Platforms (DCPs) that transmit a variety of data to the Direct Readout Terminal (DROT) and the backup Direct Readout Ground Station (DRGS) in Menlo Park. Seventy-three of these DCPs transmit data at 10-minute intervals on two exclusively assigned random channels, which are being utilized under a special agreement with NESDIS. The remainder of the DCPs report at standard 3 or 4-hour intervals as assigned by NESDIS. This system transmits data from all types of low-frequency instruments including dilatometers, creepmeters, strainmeters, water-level meters, magnetometers, tiltmeters, and related measurements. One of the first DCP's installed has been in continuous operation, with no repairs and little maintenance, for more than 3300 days.

2. Networks of tiltmeters, creepmeters and shallow strainmeters have been maintained in various regions of interest in California. A network of tiltmeters located at seven sites monitor crustal deformation within the Long Valley caldera. Roger Bilham of the University of Colorado and Jon Beaven of Lamont-Doherty installed a very long baseline tiltmeter in Long Valley. This project provided three DCP's to collect the data and return it to Menlo Park via GOES satellite. We also monitor the data received to keep track of deformation within the caldera, comparing results frequently with the USGS tiltmeter array.

3. Creepmeters located along the Hayward, Calaveras and San Andreas faults between Berkeley and the Parkfield area are maintained in cooperation with the Fault Zone Tectonics project. A shallow strainmeter is located near Parkfield, while observatory type tiltmeters and strainmeters are sited at the Presidio Vault in San Francisco, and a tiltmeter is installed in the Byerly Seismographic Vault at Berkeley. Data from these instruments are telemetered to Menlo Park via the GOES satellite.

4. A system to backup the satellite telemetry system with non-volatile, solid-state memory and dialup or dedicated telephonic communications path is currently deployed at the Long-baseline tiltmeter at Long Valley caldera. Included in this system is the capability to lock the DCP timing to a radio time standard. This feature enables more efficient utilization of the assigned satellite bandwidth.

5. A low-cost, short-haul digital telemetry system utilizing UHF radios, packet controllers and off-the-shelf digital data converters, is currently in use in Parkfield monitoring the tilt of monuments that support the reflectors that constitute the 2-color laser network. This system, components for which cost less than $1500 per site, automatically polls the remote sites and transfers the data to a computer file, calculating the mean and standard error in the process. The system, including the tiltmeters, can easily be removed and transported to other locations.
7. The Governor's Office of Emergency Services installed an OASIS (Operational Area Satellite Information System) station at USGS Menlo Park Headquarters to facilitate rapid transfer of seismological, geological and geotechnical data and information to emergency managers in the event of a damaging earthquake anywhere in California.

8. Contributed to a draft Branch plan for post-earthquake investigations following to facilitate coordination and logistics following large earthquakes.

Results

1. Conducted regional monitoring of deformation in Central California, Parkfield, and the Long Valley caldera areas. Maintained and operated instruments and associated telemetry systems in those regions.

2. Conducted advisory activities for the Regional Interagency Steering Committee (RISC), which is convened bimonthly by FEMA to accomplish and coordinate regional planning for earthquake preparedness and response. Coordinated scientific input to emergency responders following the Cape Mendocino earthquakes and the Landers/Big Bear earthquakes. Served on the State/Federal Hazard Mitigation Survey Team for the Landers/Big Bear earthquake disaster. Met with the Governor's Office of Emergency Services to discuss the use of seismological and geotechnical data in emergency management, and the use of Geographic Information Systems technology for that purpose. Participated in CONCERT (Coordinating Organizations for Northern California Earthquake Research and Technology) workshop and other activities.

Reports

The Wasatch fault zone is recognized as the most active fault zone in Utah, and the most likely source of future large, surface-faulting earthquakes to affect the populous Wasatch Front. Because of this, the U.S. Geological Survey (USGS), under the Utah NEHRP, published detailed surficial-geologic and fault maps for the northern four of the five most active central segments of the Wasatch fault (Machette, 1989; Nelson and Personius, 1990; Personius, and Scott, 1990). These maps are of great value to the Utah engineering- and environmental-geologic community, and local governments. The maps have been the basis for statewide hazard-map compilations, detailed site investigations for critical facilities, and local government geologic-hazards ordinances.

Geologic mapping of the Nephi segment, the fifth of the five active central Wasatch fault zone segments, is being conducted by the Utah Geological Survey under a NEHRP contract. The mapping begins at Payson (the southern edge of the Provo segment), and continues south to Nephi. Surficial-geologic-map units will be similar to those used in USGS fault-segment maps. Mapping is being done on 1:20,000-scale (1970) low-sun-angle and 1:24,000-scale (1958) air photos, and will be compiled onto 1:24,000-scale topographic base maps. Field checking of our air-photo mapping will include detailed study, logging, and sampling of natural exposures. Final publication will be a 1:50,000-scale colored map, in a format consistent with the USGS fault maps.

In addition to geologic mapping, we will identify sites for further detailed subsurface paleoseismic studies. The most recent surface-faulting earthquake on the Wasatch fault may have occurred on the Nephi segment 300-500 years ago, although better time constraints on the age of this event are needed. We will attempt to identify pre- and post-event geologic units that may be age dated to better constrain the MRE and other faulting events.

As of September 1993, air-photo mapping is complete. Detailed field checking is underway and will be completed by late October 1993. Several natural exposures have been selected as potential radiocarbon sampling localities. New exposures created by channel erosion in the early 1980s contain materials suitable for radiocarbon dating, and may better constrain the timing of faulting events on the Nephi segment.
REFERENCES


Investigations

We are continuing our analysis of 3-component digital seismic data recorded in southern Hawaii by the 1990 PASSCAL experiment on Hawaii (Project ALOHA), supplemented with data from the Hawaiian Volcano Observatory (HVO) seismic network, to determine the nature, extent, and spatial variability of shear-wave polarization and splitting in local microearthquake seismograms. We have hypothesized that tectonic stress will be the dominant contributor to shear wave splitting, and are endeavoring to carefully test this hypothesis. Significant levels of stress must be prevalent throughout much of southern Hawaii, as moderate to large earthquakes occur there regularly, and a great earthquake struck there in 1868. The availability of data from widely distributed events gives us the opportunity to investigate any changes in shear wave polarization and delay time as functions of event depth, epicentral distance, and azimuth.

In addition to our examination of spatial variability of shear wave splitting we are investigating the possible temporal difference in shear wave splitting in the Kaoiki region by examining events recorded before and after the 1983 M 6.7 event (Figure 1). To determine if there is a significant change in shear wave splitting, we are comparing the leading shear wave polarizations and delay times between split shear waves from events recorded by the 3-component HVO seismic station AIN located 6 km from the 1983 event epicenter before, shortly after, and one year after the earthquake.

Results

Figure 2 from Munson et al. [1993] shows that the leading shear wave polarizations at stations in the Kaoiki region agree with the direction of the maximum horizontal compressive stress ($\sigma_H$) determined from focal mechanism studies [Wyss et al., 1992 and Okubo et al., 1992] and field observations of ground rupture [Jackson et al.,
1992]. For the Bird Park (BP) array, in the Kaoiki region, the relationship between delay time and event depth shows evidence for both shallow and weaker pervasive anisotropy (Figure 3). The correlation between delays and event depth is much weaker for the Ainapo (AN) array than for BP, however a smaller slope is apparent. Conservative estimates of the crack densities for the BP and AN arrays are \( e = 12\% \) and \( e = 6\% \) respectively. In the Hilea region, the leading shear wave polarization for the Punaluu Gulch array differs by approximately 30° from the direction of \( \sigma_H \) determined by a focal mechanism study by Liang and Wyss [1991], while the Waihaka Gulch array shows no predominant polarization direction (Figure 2). No correlation between delay time and event depth was observed for either of the two Hilea arrays (Figure 3).

Events recorded during the 1990 ALOHA deployment that were used in our initial analysis of shear wave splitting have been relocated using P and S arrival times from the HVO seismic network and S-P arrival times from the ALOHA seismic arrays. Significant depth changes (and reductions in hypocenter uncertainties) resulted for many of these earthquakes when the ALOHA data were included in the location calculation. However, the revised depths did not result in any change in the correlations between event depth and delay time for the arrays.

Munson et al. [1993] reported a leading shear wave polarization of N99°E ± 7° and a delay time of 169 ± 30 ms for the Ainapo array. We have determined that the average leading shear wave polarization and delay time for events recorded prior to the 1983 Kaoiki event by the HVO seismic station AIN are N88°E ± 12° and 181 ± 18 ms, respectively, in general agreement with the results reported by Booth et al. [1992]. We are presently analyzing aftershocks from the 1983 event and plan to examine events from late 1984 to seek possible temporal changes in delay times at AIN.

References

**Contract Publications:**


Figure 1. Location of the four ALOHA arrays (triangles) along with a map (top) and cross-section view (bottom) of the earthquakes used in this study. The size of the boxes scale with magnitude, from $M = 0.5$ to $M = 6.7$. Location of HVO station AIN is shown by the shaded triangle.
Figure 2. Polarization directions of the first-arriving shear waves from the four arrays displayed as equal-area rose diagrams. The polarizations of shear wave arrivals that were followed by a clearly identifiable second shear wave arrival are shown in black (first number); those without (second number) are shown in grey. $\sigma_H$ orientations are shown for SE Kaoiki [Wyss et al., 1992] and Hilea [Liang and Wyss, 1991].
Figure 3. Delay time versus event depth for the four arrays. Least squares fits to the data (solid lines) and their correlation coefficients, $\rho$, are shown for the BP and AN arrays.
Late Pleistocene and Holocene Earthquake-Induced Liquefaction in the Wabash Valley of Southern Indiana

14-08-0001-G2117
Program Element II.5
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Introduction

Paleoliquefaction features (dikes, sills, sand-blows) induced by strong earthquake shaking during the Holocene were first documented in the Wabash River Valley in 1990 (Obermeier et al. 1991). During 1991 and 1992 the authors conducted systematic surveys of riverbank and sand pit exposures of late Pleistocene and Holocene sediments throughout southwestern, west-central, and south-central Indiana, as well as the Illinois shore of the Wabash River in southeastern Illinois. Almost 1,100 exposures were examined in these years, resulting in the discovery of 296 paleoliquefaction features at 63 sites. The results of the 1991 and 1992 research are summarized by Munson et al. (1992, 1993) and Obermeier et al. (1992, 1993).

1993 Investigations

Research in 1993 was concentrated on two aspects. First, surveys were continued along the southern, eastern, and northern margins of the distribution of paleoliquefaction as known by surveys in previous years, as well as along several creeks within the known distribution. An additional 13 paleoliquefaction sites were discovered as a result. Furthermore, because surveys were extended 40 to 60 km to the north, northeast and southeast beyond the areas where liquefaction features had been found (Figure 1), it greatly increased confidence that the boundaries had been delimited.

The second part of the research was a concerted effort to date the liquefaction events recorded at the 76 sites. This involved re-examination of most of the sites for the purposes of determining the stratigraphic position of the features in their geological, geomorphological, and pedological contexts and the collection of additional associated radiocarbon samples and chronologically diagnostic archaeological artifacts and residues.

Results

Distributional data, stratigraphy, 49 radiocarbon dates from 30 paleoliquefaction sites, and archaeological samples from 25 sites are the basis for concluding that at least seven earthquakes within the past 20,000 years were centered in or near southern Indiana and were of sufficient magnitude to cause susceptible sediments to liquefy and flow.

(1) Central and Lower Wabash Valley: $6,100 \pm 200$ BP

The paleoliquefaction features at the majority of the sites discovered in southern Indiana, and the largest dikes and sand-blows, resulted from this event. Numerous very large dikes (>60 cm wide, maximum 250 cm wide) with extensive sand-blows occur at sites within an area from 15 km north to 20 km southwest of Vincennes, Indiana. Dike sizes
generally decrease to the south, east, and north of this central area, but dikes > 15 cm wide, commonly with preserved sand-blows, are found 85 km southwest, 125 km northeast, and 140 km north of Vincennes. The total known distribution of liquefaction features that resulted from this event, including small dikes (<5 cm wide) without preserved blows, is about 250 km southwest-northeast.

Dikes and sills that resulted from this earthquake penetrate early Holocene sediments, and where sand-blows are preserved they are invariably buried by middle and late Holocene overbank alluvium. Radiocarbon dates from sites in the vicinity of Vincennes, as well as from sites 70 km southwest and 85 km northeast of Vincennes, suggest that the large dikes and sand-blows formed after 6,300 BP but before 5,900 BP. Dikes at sites 100-150 km north and northeast of Vincennes are not as tightly bracketed in time, but because they also penetrate early Holocene sediments and their blows are superimposed upon by middle and late Holocene sediments and Late Archaic Period (5,000-2,500 BP) archaeological sites it is assumed that they were formed during the same event.

Obermeier et al. (1993) have estimated that the magnitude of this earthquake was equal to or greater than $M_w$ 7.5.

(2) Lower Wabash Valley: 12,000 ± 2,000 BP

At seven sites in the lower Wabash River and lower White River valleys dikes penetrate sediments of low terraces that, on the basis of radiocarbon dates and archaeological associations, were deposited between 14,000 and 11,000 BP. By 10,000 BP downcutting of the rivers had lowered normal water table to 1 to 2 m below the top of the sand-gravel substratum at these sites; because saturated granular materials are necessary for liquefaction and flowage to occur, we assume that the dikes formed before 10,000 BP.

The largest observed dikes (30-35 cm wide) from this earthquake occur at sites within a 50 km diameter area centered about 7 km south of the confluence of White River with the Wabash River, and the total known distribution of liquefaction features is about 110 km northeast-southwest.

(3) Upper East Fork Valley: 3,000 ± 1,000 BP

Paleoliquefaction features, some of large size (maximum dike width 63 cm), are found at 17 sites within a 50 km diameter area in the valley of the East Fork and its tributaries in south-central Indiana. Some of the smaller dikes penetrate late Pleistocene and early Holocene sediments, and consequently might have resulted from strong shaking that was centered 150 km to the west-southwest (i.e., earthquakes #1 and/or #2, above). Other dikes, however, including some of the larger ones, penetrate sediments radiocarbon dated 4,170 ± 70 BP and 4,230 ± 70 BP, indicating a later date and a more local source for strong shaking. Dikes at one site are erosionally truncated by a deposit dated 1,630 ± 70 BP.

(4) Lower White River Valley, Site CC: <4,440 ± 80 BP

Two small dikes (1 and 5 cm wide) are found at Site CC in the lower White River valley. A log in the gravelly sand source material dates 4,440 ± 80 BP, indicating that liquefaction here substantially post-dated the strong paleoearthquake centered near Vincennes. Although the dikes might have resulted from the 3,000 ± 1,000 BP earthquake in the East Fork valley, the absence of evidence of liquefaction in the numerous exposures of penecontemporary sediments in the 100 km that separate this site from the East Fork cluster of dikes would seem to render this possibility unlikely. Somewhat more plausible is the possibility that dikes at Site CC and at Site ELI (discussed below), located 50 km to the
northeast, resulted from a single, moderately strong, late Holocene earthquake centered somewhere between these two sites. However, this scenario also suffers from the fact that no evidence of liquefaction has been found at the numerous exposures of penecontemporary deposits between Site CC and Site EL1. Therefore, the most likely explanation is that the small dikes resulted from an earthquake centered near Site CC that had a magnitude only slightly higher than the threshold required to cause susceptible sediments to liquefy.

(5) Lower White River Valley, Site EL1: $<2,580 \pm 70$ BP

Site EL1, also in the lower White River valley, has four small dikes (1 to 3 cm wide) that penetrate sediments radiocarbon dated $2,580 \pm 70$. For the same reasons just discussed for Site CC, we think that liquefaction at Site EL1 resulted from a local earthquake of a magnitude equal to or only slightly greater than the threshold required to cause liquefaction.

(6) Central White River Valley, Site IC: Late (?) Holocene

At Site IC in the central White River valley two liquefaction events, probably widely separated in time, extruded sand into a single medium-sized dike. During the first episode of strong shaking a sand dike 6 cm wide penetrated upward 2.5 m through the late Pleistocene or early Holocene loam topstratum. The extruded sand from this event has been greatly modified, almost to the base of the dike, by "beta-B," iron-oxide, and clay enrichment. Subsequently, additional sand flowed upward into the dike, but only to a height of 1.5 m above the source materials; the extruded sand from this event has not been significantly modified by pedogenesis. We assume that the first liquefaction event resulted from strong shaking centered near Vincennes at $6,100 \pm 200$ BP. The absence of evidence for two liquefaction events in nearby exposures of Holocene sediments suggests that the second dike filling resulted from a "liquefaction-threshold" magnitude earthquake centered near Site IC.

(7) Central White River Valley, Site MO: $20,000 \pm 1,000$ BP

Two small dikes (1 and 3 cm wide) at Site MO, also located in the central White River valley, can be closely bracketed in time. They penetrate proglacial lake sediments that were deposited $20,000-21,000$ BP. By $19,000$ BP these sediments had been so thickly capped by glacial outwash and loess that liquefaction would have been suppressed. Because this exposure is unique, it has not been possible to determine if dikes were formed at other locations at this time; the liquefaction features at Site MO might have resulted from a "liquefaction-threshold" magnitude earthquake centered near the site, or, alternatively, the features might be at the margin of liquefaction caused by a larger earthquake centered some distance from the Site MO.

(8?) Site CD

At Site CD a 1 cm wide sand dike penetrates Illinoian till and is erosionally truncated by a sand- and gravel-filled Holocene channel. The base of the dike lies more than 2 m below water level and cannot be observed. Various explanations are equally plausible: (1) the dike formed during the $6,100 \pm 200$ BP earthquake centered near Vincennes; (2) it resulted from the same earthquake as the dikes at Site MO; (3) it resulted from yet another strong earthquake in this area sometime after $100,000$ BP; or (4) it is not an earthquake-induced feature, but rather is a desiccation crack that has filled with sand from the top down.

Related Research

Several research projects related to the investigations described above are being carried out by others. The principal investigators for the Wabash Valley study have
cooperated with: (1) J.R. Martin and E.C. Pond of Virginia Polytechnic University, who are conducting geophysical studies at paleoliquefaction sites associated with the three prehistoric earthquakes that produced the most areally extensive liquefaction; (2) S.F. Obermeier of the USGS, who is continuing surveys in Illinois to identify paleoliquefaction sites primarily southwest of the Wabash Valley; and (3) the Illinois State Museum, which has initiated additional paleoliquefaction surveys west of the Wabash Valley.

Additionally, the Wabash Valley investigators have worked closely with D.L. Eggert of the Indiana Geological Survey and others (Eggert et al., in press) to compile current information on seismic hazards and to assess the suitability of current building and construction requirements in Indiana.

Reports


Papers Presented


Figure 1. Map showing areas searched, locations of paleoliquefaction sites, and estimated limits in Indiana of liquefaction from three large prehistoric earthquakes.
INVESTIGATIONS

The project consists of two components: Nelson's study of coseismic changes in late Holocene sea level as revealed by tidal-marsh stratigraphy, and Personius' study of fluvial terrace remnants along major Coast Range rivers to determine styles and rates of late Quaternary deformation. Both components will help define the potential hazard from great subduction earthquakes in the U.S. Pacific Northwest.

RESULTS

Coseismic changes in late Holocene sea level

Has subduction of the Juan de Fuca plate beneath the North America plate in the Pacific Northwest produced great (M>8) earthquakes during the late Holocene? Records of the past 200 years yield no evidence of great plate-interface earthquakes in the Cascadia subduction zone. But along the coasts of Oregon and Washington peaty, tidal-wetland soils are interbedded with mud in estuarine stratigraphic sequences, and the submergence (relative rise of sea level) of some of these soils seems too widespread (>100 km), too large (>1 m), and too sudden (<10 years) to be attributed to any process except coseismic subsidence. How large were the Cascadia plate-interface earthquakes that produced coastal subsidence and how often did they occur? Such questions are critical for earthquake hazard assessment in the Pacific Northwest (PNW).

Nelson's research in FY93 focused on the following two questions:

Objective 1: Were the peaty units interbedded with estuarine mud in late Holocene tidal-marsh stratigraphic sequences in the Pacific Northwest submerged and buried during the same 50- to 300-yr-long periods?

Peaty stratigraphic units may have been submerged and buried during great (M>8) subduction earthquakes, smaller upper-plate earthquakes, or by nonseismic processes. Precise
II

radiocarbon dating should help distinguish among these alternatives by showing whether units at different sites were submerged at different times.

Final results on our precise multiple AMS dating of the youngest (250 BP) buried peaty soil at seven sites that span 440 km of the Oregon and Washington coasts do not preclude regional subsidence during the same earthquake (Fig. 1). Dated samples are the rooted stem and leaf bases of individual tidal-marsh plants (*Potentilla pacifica* and *Juncus* sp.) suddenly submerged about A.D. 1700. Our mean 14C ages are more precise than expected with standard deviations of only ±17 yr. Mean ages in central and southern Oregon appear slightly older than ages farther north and than the very precise tree-ring ages obtained by Atwater and others on the same soil at three of the sites. But these differences are more likely due to systematic differences in reported 14C ages of a few hundred years between the New Zealand and Seattle laboratories than to real age differences. Calibration of the mean ages indicates that the buried plants at all sites died after A.D. 1660. The history of settlement in the region suggests there would be a historical record of any great earthquake more recent than A.D. 1750.

In July Nelson reviewed the stratigraphy of the tsunami sand associated with the 250 BP subsided soil at Tofino on the west coast of Vancouver Island with John Clague (Geological Survey of Canada). No rooted plant fossils at the top of the soil were found despite two days of searching at four sites. However, at Port Alberni we found *Triglochin* fossils at the base of a sand bed thought to have been deposited by the 250 BP tsunami. We collected enough of these fossils for AMS analysis, but advised Clague that so many fossils were present at that site that a more accurate age could be obtained with the high-precision conventional radiocarbon method developed by Minze Stuiver. Later, with the help of several friends, Clague dug a 2X4-m pit at this site and collected enough fossils for the high-precision age. If this age is similar to our ages at the seven 250 BP sites in Oregon and Washington, all ages would not preclude a 700-km-long rupture about 300 years ago. These ages combined with those of Atwater and Carver on trees in Humboldt Bay, California, would not preclude a 950-km-long rupture.

In May and September Nelson collected fresh samples of plant fossils from the 1500 BP soil at Netarts Bay, Oregon, and from a similar-aged soil and the 1700 BP soil at the Naselle River in Washington. Analysis of the 1500 BP soil at both sites will help show whether all buried marsh soils in northern Oregon and Washington correlate along hundreds of kilometers of coast or whether some less well developed soils were submerged at different times at different sites. The 1700 BP soils at these sites are similar to the well-developed 250 BP soils and so they are more likely to be the same age than the less well developed 1500 BP soils. Samples from both soils have been cleaned, specially pretreated, and submited for AMS analysis. These experiments should help answer questions about whether average great earthquake recurrence is about 300 yr or closer to 1500 yr in northern Oregon and Washington.

Objective 2: *Were most of the peaty units in marsh stratigraphic sequences in the PNW submerged and buried during coseismic subsidence or were many of these units buried by nonseismic coastal processes?*

One of the central concerns of our marsh stratigraphic studies in Oregon discussed in earlier reports and publications, was the degree to which marsh stratigraphic sequences in the PNW were similar to those of some passive continental margins, such as the U.S. Atlantic coast, and, therefore, whether many buried peaty stratigraphic units in the PNW might have a nonseismic origin. Some aspects of Nelson's FY92 studies with Ian Shennan, Antony Long, and other sea-
level researchers at the Department of Geography, University of Durham, England, have been summarized in the draft of a review paper by Nelson, Shennan, and Long, intended for the *Journal of Geophysical Research*. Because of the different historical traditions of sea-level research in the U.S. and U.K., this paper may have an influence on the direction of Holocene sea-level studies in the PNW, and possibly on the U.S Atlantic coast as well. Nelson is also writing a second paper to be submitted to the *Geological Society of America Bulletin* that describes paleoecologic analyses and interpretations of a core from the South Slough arm of Coos Bay and their implications for earthquake hazard analysis in Oregon.

*Deformation of fluvial terraces*

Personius is completing his analysis of fluvial terraces in the Oregon Coast Range. This analysis has two main objectives: (1) to search for active folds and faults, and (2) to analyze stream (bedrock) incision rates for evidence of differential uplift. Both aspects of this research are aimed at helping to define intermediate-term (late Pleistocene and Holocene) rates and styles of deformation in the on-land portion of the forearc of the Cascadia subduction zone. Such information can help define the tectonic settings of tidal-marsh and geodetic studies in the region.

A single example of an active structure has been found in the central Coast Range, a north-trending anticline in Eocene bedrock on the Siuslaw River that has warped the overlying fluvial terraces. However, there is no evidence that this or any other structure has been active in late Pleistocene or Holocene time. The poor preservation of terraces in the Coast Range indicates that other active structures may have gone undetected, but the presence of an undeformed, relatively continuous latest Pleistocene-early Holocene terrace along most rivers precludes the presence of rapidly deforming Holocene structures. The large area affected by the anticline on the Siuslaw River (over 20 km wide) indicates that active folds should be easy to detect on profiles of older stream terraces.

Personius' research in FY 93 focused on the following question:

**Objective 3:** *How do the rates of late Quaternary bedrock incision vary along streams in the Oregon Coast Range, and what do variations in incision rates tell us about differences in the subduction process along the Cascadia subduction zone?*

Personius is completing this project objective. Three weeks of fieldwork in August were focused on making additional stream incision measurements along northern Coast Range rivers, and making rock mass strength measurements of incised bedrock in the region. Using this new data he will soon complete analysis of patterns of regional incision and uplift for a period of time (7-40 ka) that is intermediate between previous studies of 80-125 ka marine terraces and historic (60 yr) geodetic data. The most significant result of this work is that measurements of intermediate-term (7-40 ka) bedrock stream incision in the northern Coast Range are 2-3 times higher than incision rates along central Coast Range rivers. These variations in incision rates are most evident near the latitude of Newport, where a steep gradient is present between lower rates to the south and higher rates to the north. The sharp contrast in incision rates appears to be a function of differential uplift of the Oregon Coast Range, and is probably not related to differences in the erodability of bedrock or climatic influences in stream incision. The cause of these variations in uplift is unknown, but it is probably caused either by north-south
compression in the overriding North America plate or by changes in the geometry or behavior of the subducting Juan de Fuca plate.

These incision results may aid in the interpretations of the tectonic settings of coastal marsh sites in Oregon and Washington, and they should be useful in determining the relative roles of uplift and subsidence in the earthquake cycle during late Holocene earthquakes. Unfortunately, the stream incision technique developed by Personius can only be applied to nontidal reaches of Coast Range streams, because sea-level fluctuations have probably influenced stream incision on the tidal reaches of those streams. Thus stream incision cannot be used to determine whether individual coastal marshes have had histories of net uplift or subsidence in the Holocene, although regional incision data clearly indicate that net Holocene uplift rates in the northern Oregon Coast Range are substantially higher than at similar sites in central Oregon.

Research results were presented by Personius at the joint Rocky Mountain/Cordilleran section GSA meeting in May, 1993, and are the subject of a paper presently in preparation that will be submitted to the Journal of Geophysical Research. A second paper that discusses the climatic significance of a 10 ka terrace present in most drainages in the Oregon Coast Range was published in the November 1993 issue of the journal Quaternary Research.
REPORTS PUBLISHED


Figure 1. Mean ages (in radiocarbon years at one standard deviation) and corresponding calibrated-age time intervals (at two standard deviations) for sites where we have analyzed marsh plant fossils rooted in the top of the marsh soil that was suddenly submerged about 250 BP. The control sample of wood from the outer ring of a tree killed by submergence at the Copalis River allowed us to estimate the error multiplier for all samples at <1. Because of the wide variation in the $^{14}$C calibration curve in the past 300 years the $^{14}$C ages correspond to several time intervals during the past 300 years. History does not record sudden submergence of the PNW coast, such as caused by great earthquakes, in the past 200 years. This suggests that the oldest of the time intervals corresponds to the true age of the samples. Because the oldest intervals of all samples overlap, we cannot conclude that any samples differ in age. The apparent small age difference between the more precise tree-ring ages of Atwater and others (width of vertical bar) now available from three sites (Copalis, Niawiakum, and Nehalem) and some AMS ages may be due to a systematic difference in young ages between laboratories.
ANALYSIS OF THE 1992 M6.1 JOSHUA TREE EARTHQUAKE SEQUENCE AND ITS RELATION TO THE SOUTHERN SAN ANDREAS FAULT, CALIFORNIA

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Program Element II.2

INVESTIGATIONS UNDERTAKEN

Two deployments of portable digital instruments were made in 1992 following the April M6.1 Joshua Tree event and again in June following the M7.4 Landers and M6.5 Big Bear events. Both deployments were successful, largely because of the tremendous cooperation between the various participating SCEC institutions involved, including Caltech, UCSB, UCSD, USC, USGS, IRIS/PASSCAL, and SDSU.

22 April M6.1 Joshua Tree Earthquake

Five SCEC instruments were initially deployed within 6.5 hours of the April 22 M6.1 Joshua Tree mainshock. UCSB assisted in the deployment and maintenance of these sites. Six PASSCAL recorders were added to the deployment in the following days. The array was maintained until early June and collected about 5-6 Gbytes of raw digital data. At ICS, we corrected timing and performed event association on 3-4 Gbytes of data left after initial data processing and reduction. Over 10,700 events were associated, and the data were made available to the SCEC Data Center at Caltech.

28 June M7.4 Landers and M6.5 Big Bear Earthquakes

Nine PBIC DAS's were deployed for this aftershock sequence. PASSCAL supplemented the SCEC array with 10 DAS's in the days following the mainshock. SCEC member institutions, including UCSB, worked together to deploy and maintain the array. Once fully deployed, the array consisted of 18 sites including 3 STS-2 and 2 CMG-3 broadband sensors. A prototype field computer was used to perform initial field quality control of the data. Over 8 Gbytes of raw data were collected. Data processing, event association and timing corrections were performed at UCSD. Over 8,000 events were associated, and the data made available to the SCEC Data Center at Caltech.

FY1993 RESEARCH RESULTS

1. Changes in Attitude - Changes in Latitude: What Happened to the Faults in the Joshua Tree Area Before and After the M7.4 Landers Mainshock?

CRAIG NICHOLSON, RUTH A. HARRIS, AND ROBERT W. SIMPSON

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault. It was followed by over 6,000 M>1 aftershocks. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the Landers earthquake on June 28. From the distribution of aftershocks and directivity effects, the mainshock ruptured unilaterally to the north along a fault about 15 km long. The focal mechanism indicated right-slip on a plane striking N14°W, dipping 80°W, with a rake of 175°. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. Aftershocks continued to migrate to the north and south following the mainshock, and ultimately extended from the southern San Andreas fault near the Indio Hills to the Pinto Mt fault. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June M7.5 Landers event, and has not yet resumed. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. We investigate possible explanations for this change in the pattern of earthquake activity as a result of inferred stress changes induced by the Landers mainshock and some of its larger aftershocks.
2. Joint 3-D Tomography Using Seismic And Gravity Data Of The 1992 Southern California Sequence: Constraints On Dynamic Earthquake Ruptures?

JONATHAN M. LEES AND CRAIG NICHOLSON

Linear tomographic inversion of P-waves from the recent 1992 Southern California earthquakes is used to produce 3-D images of subsurface velocity. The 1992 dataset, augmented by 1986 M5.9 North Palm Springs earthquakes, consists of 6458 high-quality events providing 76,306 raypaths for inversion. The target area consists of a 104×104×32 km³ volume divided into 52×52×10 rectilinear blocks. Laplacian regularization was applied and the residual RMS misfit was reduced by ~40%. Significant velocity perturbations are observed that correlate with rupture properties of recent major earthquakes. Preliminary results indicate a low-velocity anomaly separates dynamic rupture of the M6.5 Big Bear event from the M7.4 Landers mainshock; a similar low-velocity region along the Pinto Mt fault separates the April M6.1 Joshua Tree sequence from the Landers rupture. High-velocity anomalies occur at or near the nucleation sites of all 4 recent mainshocks (North Palm Springs-Joshua Tree-Landers-Big Bear). A high-velocity anomaly is present along the San Andreas fault between 5-12 km depth through San Gorgonio Pass; this high-velocity area may define an asperity where stress is concentrated. To test model reliability, a joint inversion of seismic and gravity data was performed. Gravity data can be used by assuming a linear relation between density and velocity perturbations. Gravity may be important to subsurface structure because the Landers rupture follows a strong gravity gradient. Gravity also helps constrain near-surface regions of the model where incident rays are nearly vertical and seismic resolution is poor. The joint 3-D model is required to fit both seismic data and isostatic gravity anomalies to a specified degree of misfit. A joint tomographic inversion in which 40% of seismic data residual misfit and ~80% of the gravity anomalies are explained does not differ significantly from previous models. These results suggest that high-resolution 3-D tomography may be a more effective means of segmenting active faults at depths than near-surface mapping.

3. The April 1992 M6.1 Joshua Tree Earthquake Sequence: Analysis of Portable Data and 3-D Tomographic Inversion

AARON MARTIN, CRAIG NICHOLSON, AND JONATHAN M. LEES

The M6.1 Joshua Tree earthquake of 23 April 1992 occurred about 8 km northeast of the southern San Andreas fault and about 20 km south of the Pinto Mt fault at a depth of 12-13 km. The mainshock was followed by over 6,000 M>1 aftershocks recorded by the permanent regional network and an 11-element portable array deployed by the Southern California Earthquake Center. No surface rupture for this sequence was found; although ground fractures were discovered in this area after the M7.4 Landers earthquake and its large aftershocks of June 28. We relocated 10,570 events between 23 April and 24 July using the data from the regional network; and determined 3,030 single-event focal mechanisms with 15 or more first-motions. A large number of aftershocks occurred off the mainshock rupture plane on adjacent secondary structures that strike either sub-parallel to the Joshua Tree mainshock plane or on relatively short, left-lateral faults that strike at high angles to the mainshock plane. The northern 15-km section of the aftershock zone had a strike more nearly N10°E. Seismicity on this fracture network ceased in the hours prior to the 28 June Landers event, and did not resume. Instead, the Landers mainshock appears to have caused the activation of a new fracture network located farther west, that intersects the previous Joshua Tree activity in the area of the Joshua Tree mainshock, and is oriented more nearly N15°W. This change in activity corresponds to a net tilt of about 30°-40° of the least-principal stress (σ₃) down to the northwest towards the Landers mainshock. Much of this later activity also coincides with a first-order discontinuity in 3-D velocity structure imaged by tomographic inversion of P-wave arrival times [Lees and Nicholson, 1993]. Phase arrivals from nearly 600 events recorded by at least 5 or more portable digital instruments were used in a comparison of earthquake hypocentral locations. Relocated hypocenters are typically deeper and located farther west, if both portable and permanent network data are used. The portable phase data were also used in a tomographic inversion for 3-D P-wave velocity structure specific to the Joshua Tree area. Over 33,000 rays from 6,000 local events were inverted for 3-D velocity perturbations relative to a 1-D homogeneous layered model. The velocity anomalies imaged by the 3-D inversion exhibit a high correlation to active faults delineated by earthquake hypocenters and focal mechanisms.
REPORTS PUBLISHED (1992-1993)


PALEOSEISMIC AND GEOARCHAEOLOGIC INVESTIGATIONS OF THE SAN GREGORIO FAULT, SEAL COVE, CALIFORNIA

Award No. 1434-93-G-2275
Program Element II.5
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Evaluating Earthquake Potential

Technical Approach

We are conducting a one-year program to assess the paleoseismic characteristics of the onshore length of the northern San Gregorio fault between Half Moon Bay and Moss Beach, also known as the Seal Cove fault, about 20 kilometers south of San Francisco, California. This progress report summarizes our technical approach and the setting of our research site. Because we are currently conducting subsurface explorations, we do not yet have results.

This project involves phased geologic and archaeologic programs designed to meet our objective to reconstruct the nature and history of earthquakes along the northern San Gregorio fault. We are focusing on two well-preserved archaeologic sites that appear to be right-laterally offset by the San Gregorio fault in James Fitzgerald Marine Reserve, located along the San Mateo County coast at Seal Cove. The study will integrate results of a multidisciplinary program of lithostratigraphy, ethnostratigraphy, pedostratigraphy, and biostratigraphy to evaluate the middle to late Holocene history of the northern San Gregorio fault.

Our approach is similar to that taken in our investigations of the San Andreas fault at Fort Ross (Noller et al., 1993). We conduct conventional paleoseismic investigations within the context of the area's long-term human occupation (ca. 2,000 - 5,000 years). We are applying new paleoseismic techniques we developed at Fort Ross in a four-phase paleoseismic and geoarchaeologic investigation of the San Gregorio fault: (1) a detailed strip map at a scale of 1:600 of the surficial geology and archaeology along the San Gregorio fault between Seal Cove and Pillar Point; (2) detailed survey of archaeological sites; (3) characterization of near-surface geology; and (4) data analysis and reporting. On the basis of our field reconnaissance, this area has an excellent combination of geologic, geomorphic, and cultural features to assess fault characteristics. In particular, we anticipate that the geologic data will provide information on the number and timing of events and the archaeologic data will provide constraints on middle to late Holocene slip rate.

Research Site Setting

Two sites along this reach of the fault promise to yield a continuous record of paleoseismic activity. Based on our survey of the Reserve, these sites host an abundant concentration of archaeological midden deposits that cross the San Gregorio fault. One archaeological site in particular straddles a single trace of the fault marked by a linear depression, and appears to be a multi-component (i.e., several artifactual assemblages) site that was repeatedly occupied. Nearby archaeological sites have an Emeryville artifact assemblage that dates from ca. 2,000 - 3,000 years B.P. We expect this site to have a similar, if not older, artifact assemblage. Surface scatter at this site includes projectile points, stone tools and historic artifacts. The number of artifacts present at this site are...
quite extraordinary; our surface survey showed several ground and mill stones, scrapers, and many shells of various types.

We have compiled and reviewed previous literature on the site geology. Published reports, state fault-evaluation reports, and consultants' reports obtained from the County of San Mateo record the near-surface stratigraphy in borehole and trench-excavation logs. We are establishing a preliminary site stratigraphy on the basis of these data.

We have constrained the location of the fault through review of previous fault investigation studies and reports. The Seal Cove fault was located by JCP (1982) in two trenches south of our primary archaeological site. In these trenches, the fault was expressed as a 2-meter-wide zone of brecciated rock and fissure fills. A subsequent fault investigation by Cleary Consultants (1990) located a narrow zone of faulting that passes through our primary archaeological site. These earlier studies did not address the problems of fault slip rate or the number and timing of previous earthquake events.

References

Cleary Consultants, Fault location investigation, Interpretive Center site, 1990.

JCP-Engineers & Geologists, Inc., Report for two lots located at the intersection of Cypress Avenue and Park Way, Moss Beach, California, 1982.

The purpose of this project is to determine where prehistoric earthquake shaking has been strong enough to form liquefaction-induced features. The threshold magnitude for significant liquefaction is about M 6. Relict liquefaction-induced features normally take the form of sand- or gravel-filled dikes and sills. The dikes and sills commonly are preserved in the recent geologic record.

Field searches for evidence of relict liquefaction were conducted this past year in two regions: the Wabash Valley Seismic Zone (of southern Illinois and Indiana), and near the coast of Washington State.

WABASH VALLEY SEISMIC ZONE

Background

The Wabash Valley Seismic Zone is a zone of diffuse seismicity centered about the Wabash Valley of Illinois and Indiana. Many small and slightly damaging earthquakes have occurred here during the 200 years of historic record. The Wabash Valley region has extensive alluvial lowlands, ranging in age from late Wisconsinan to modern. The alluvium is sand-rich, and the ground-water table has been high throughout much of the Holocene. Altogether, the setting of the valley has been conducive to formation and preservation of prehistoric liquefaction features for thousands of years. Laterally cutting rivers expose clean outcrops at many places.

Investigations

Hundreds of kilometers of outcrop throughout southern Illinois and Indiana have been examined for evidence of earthquake-induced liquefaction. Search areas were mainly in stream banks, but walls of man-made ditches and sand and gravel pits were also searched. Major streams searched were the Wabash, White, Embarras, Kaskaskia, Saline, and Eel Rivers. Significant portions of the Ohio River were also searched.

Results

Hundreds of planar, nearly vertical sand- and gravel-filled dikes that are interpreted to have been caused by earthquake-induced liquefaction have been discovered throughout southern
Illinois and southern Indiana. These dikes range in width from a few centimeters to as much as 2.5 m. The largest dikes are centered about the general area of Vincennes, Indiana; dikes strongly tend to decrease in size and abundance in all directions from the vicinity of Vincennes. Dikes in Indiana are present more than 150 kilometers from Vincennes. Geologic, archaeologic, and radiocarbon data show that most of the dikes were formed by a single large earthquake that took place in the Vincennes area sometime between 5,000 and 7,500 years ago. Three other strong earthquakes have struck during the approximate time span of the Holocene. Engineering-seismologic analysis, based on comparison of liquefaction effects with those of historic earthquakes in the Central and Eastern United States, indicates that the magnitude of the largest prehistoric earthquake was on the order of M 7.5.

Reports


COASTAL WASHINGTON STATE

Coastal Washington has been almost completely devoid of historic earthquakes. The only occurrences have been scattered small events. Yet there is the possibility that great earthquakes occur here periodically. Atwater (1987, 1992) estimates that at least two episodes of coastal subsidence have occurred in Washington State during the past 2,000 years. Strong evidence indicates that one episode occurred 300 years ago and less widespread evidence indicates that another episode occurred 1,400 to 1,900 years ago. Buried lowlands indicative of this coastal subsidence have been postulated as originating from the action of great subduction earthquakes (M ~ 8 to 9.5). The earthquakes probably originated along the Cascadia subduction zone, where the oceanic (Juan de Fuca) plate is being subducted beneath the continental (North American) plate. To test the M 8 to 9.5 hypothesis, a search for relict liquefaction features was initiated.

Investigation

The search areas (Fig. 1) are designated in two categories:

570
the Columbia River and smaller rivers. A major part of the search in the rivers was near the coast where shaking should have been strongest. Most searching in smaller rivers was in banks of the Humptulips and Chehalis Rivers.

**Results**

Many islands in the lowermost Columbia River were searched between the towns of Astoria and Bonneville Dam (Fig. 1). Most of these islands originated as large braid bars. The islands are flat, poorly drained, and swampy. Large portions are submerged during very high tides. Strong currents and wave pounding are severely eroding many islands and, as a result, are sculpting clean, vertical clay-rich banks as much as 2 meters in height, which extend from water level to top of the bank. Age at the base of the exposed clay-rich cap is less than 1,000 years at all sites tested downstream from Longview. The age is based on a radiocarbon ages on tuberous plants (genus *scirpus*) found in their growth position, just above the base. Therefore, the sediments are old enough to record shaking associated with Atwater's 300-year old downdropping event, but probably not old enough for the eposide of 1,400 to 1,900 years ago.

On many islands sand is exposed immediately beneath the clay cap. Grain sizes range from fine- to medium-grained, clean sand to clayey, silty fine sand. Clean sands appear to be widespread and commonplace. Altogether, conditions on many islands are conducive to formation of large liquefaction-induced features. Not only is the cap thin, but the ground-water table has a almost certainly been at or within a meter or so of the ground surface since the islands formed.

About 50 km of clean banks were searched for liquefaction features. More than two hundred sand-filled dikes have been found in scattered islands. The dikes vented onto a paleosol, and about 1 m of silt and clay subsequently was laid down on the vented sand. For the following reasons, all dikes are thought to have been caused by the coastal downdropping event 300 years ago: (1) the radiocarbon ages of sticks collected on the surface of venting are in the proper range; (2) trees rooted in sediments above vented sand have the same maximum ages (about 200 years); (3) dikes increase in abundance toward the coast; (4) maximum dike sizes (widths) increase toward the coast.

Only very small dikes in the Columbia River islands occur as far as 90 km inland from the coast (Deer Island). At Wallace Island, about 60 km from the coast, a preliminary geotechnical analysis of the strength of shaking indicates that bedrock accelerations were on the order of 0.1 g or less.

At least 150 km of smaller rivers were searched (Fig. 1). More than 30 km of river banks were eroded so cleanly that even very small dikes (1 cm in width) would have been observed. At many places there are two or three (pedological) weathering...
profiles stacked on top of one another, each separated by a meter or so of silt and clay. Therefore, on the basis of well-developed pedological profiles in the deposits along the banks, in combination with some radiocarbon ages, ages of many kilometers of deposits exposed in the banks much predate the 300-year old downdropping event.

Beneath a thin clay-silt cap along the smaller rivers, sandy gravels occur at almost all places. Depth to semilithified to lithified bedrock seems to range from a few meters to about 30 meters.

There is a paucity of clear-cut liquefaction induced feature within 50 km of the coast, in banks of smaller rivers. The sandy gravels of these river valleys are so coarse-grained that very strong shaking probably would be required to cause liquefaction features to form. Still, comparison of grain-size data shows that even coarser gravels (based on data in Andrus, 1993) formed large dikes and vented large quantities of sand and gravel to the surface during the 1983 Borah Peak, Idaho, earthquake (M 7.3). Peak accelerations at the Borah Peak liquefaction sites are thought to be about 0.3-0.4 g (Andrus, 1993). Thus, it would seem that a great earthquake directly beneath the coast of Washington, causing very strong shaking, should have formed numerous liquefaction-induced features in the sandy gravels. Only a few have been found within 50 km of the coast, however.

Numerous dikes have been discovered in banks of the Chehalis River, near Centralia. At least two generations of earthquakes, widely separated in time, are represented. Most of the dikes probably originated in response to the 1949 Olympia (M 7.1), which produced numerous sand blows in the Centralia area.

Reports

Obermeier, Atwater, Benson, Peterson, Moses, Pringle, and Plamer, 1993, Liquefaction about 300 years ago along tidal reaches of the Columbia River, Oregon and Washington, EOS, Transactions, American Geophysical Union, v. 74, no. 43, p. 198.

Palmer, Dickenson, Roberts, and Obermeier, 1993, Results of a reconnaissance geotechnical survey along the lower Columbia River: EOS, Transactions, American Geophysical Union, v. 74, no. 43, p. 199.


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Figure 1. Map of coastal portion of Washington State showing rivers whose banks were searched for evidence of relict liquefaction features. In the Columbia River, banks of islands were searched. These searched islands have ages between 600 and 1,000 years at most places. Sands beneath islands are fine to medium grained and are highly to moderately susceptible to liquefaction. Banks of all other streams have terrace deposits probably ranging from latest Pleistocene to modern in age; these terrace deposits generally are underlain by sandy gravels that are so coarse grained that very strong shaking probably would be required to induce widespread liquefaction.
EXPLANATION

Portions of smaller rivers that were searched extensively

Centralia
Newaukum River

Inland limit for:
- 30-cm wide dikes
- 20-cm wide dikes
- 15-cm wide dikes

Generally increasing density of small- and medium-size dikes; total absence of large dikes

Sandy River
COLLABORATIVE RESEARCH (USGS-GRA AND MODNR-DGES): SHALLOW SEISMIC REFLECTION SURVEY BENION HILLS, SOUTHEAST MISSOURI

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Award Number: 1434-93-G-2360

Program Element II.1

TECHNICAL ABSTRACT:
Shallow high-resolution seismic reflection data (Mini-Sosie) were collected along two traverses that cross the southern escarpment of the Benton Hills, in Scott County, southeastern Missouri. The surveys roughly parallel U.S. Interstate 55. The line east of I-55 is 2.6 km long and the line west of I-55 is 3.9 km long. Both traverses crossed significant local relief, much of it in off-road areas. The field work was conducted in late May and early June. The reflection data are still being processed, so we do not have final results yet.

The Benton Hills are the northeasternmost part of the Crowleys Ridge uplands of the Mississippi Embayment, and form the western side of Thebes Gap of the Mississippi River. The traverses cross areas where previous studies (Stewart, 1942) had identified north-northeast and northeast oriented faults along the margin of the escarpment. These faults involved Quaternary loess and Cretaceous or Tertiary sediments. However, others have suggested that these structures are landslides and not faults. We hope to resolve this with the reflection data. Our preliminary stratigraphic, geomorphologic, and photo-lineament investigations identify features characteristic of tectonically active alluvial basin margins (Palmer and Hoffman, 1993). Furthermore, field mapping conducted since we proposed this study, has found evidence of dextral strike-slip faulting along these north-northeast and northeast structures, which is consistent with the focal mechanisms of small and slightly damaging earthquakes centered in the Benton Hills (Richard Harrison and Arthur Schultz, in press).

This area may have faults that are capable of producing damaging earthquakes. If the reflection data indicates faulting where we suspect, that information will be used to help locate the best potential trenching sites to determine if faulting occurred during the Quaternary, its magnitude of deformation and possible repeat intervals. We have proposed this geological study for Federal Fiscal Year 1994.

References


Palmer, James R., and Hoffman, Dave, 1993, Possible late Quaternary faulting in the Benton Hills, southeastern Missouri (abs.): North-Central Section, Geological Society of America Abstracts with Program, v. 25, no. 3, p. 72

Variations in Electrical Properties Induced by Stress Along the San Andreas Fault at Parkfield, California

Grant 14-08-0001-G1808

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Introduction

We are monitoring fluctuations of resistivity with telluric currents in Parkfield. The array uses grounded telephone lines as dipoles (Figure 1). The analysis was discussed in Park [1991]. We look at daily fluctuations of the telluric coefficients relating Dipoles 1 through 6 to the reference dipoles of Dipoles 7 and 8. Thus, we are looking at relative variations, rather than absolute ones. Changes in the telluric coefficients are directly related, albeit through the response of a complex, heterogeneous earth, to changes of resistivity.

Discussion of Data

Results of the analysis for the past eleven months for Dipoles 1 through 6 are shown in Figures 2 through 7. We plot the projection of the daily fluctuation of the telluric coefficient onto the major and minor eigenvectors (upper and lower plots for each dipole, respectively) and the coherency as a measure of the data quality. The major eigenvector is aligned in the direction of the dominant electric field polarization and is roughly perpendicular to the San Andreas fault. The minor eigenvector is aligned parallel to the fault. Based on fluctuations of the projections for all of 1988 and 1989, standard deviations for the daily projections were calculated. The 95% confidence intervals (approximately $2\sigma$) are shown with dashed lines in Figures 2 through 7. These projections are further smoothed with a nine day running average which is weighted by the inverse of the square of the coherency (which is a measure of the relative noise). The error bars for each daily point are standard errors calculated from this running weighted average.

Significant deviations can be identified in one of two ways. First, points which lie outside the 95% confidence intervals can be significant. Second, deviations for which the error bars are not overlapping may be significant. For example, the major projection on Dipole 1 lies beyond the confidence interval between days 42 and 55 in 1993 (Figure 2), and error bars are not overlapping. This excursion is significant because it meets both criteria for identification and affects dipoles 3, 4, and 5 (Figures 4, 5, and 6, respectively). This excursion may have also been seen on dipole 6 (Figure 7), but the error bars are excessively large during this time period. No other significant variations were seen during 1993 including during the A level alert in November. However, we may have seen anomalous...
electric fields prior to the M4.8 earthquake in Parkfield on November 13 (day 317). We are currently checking our suspect signals against results from the other arrays.

No significant tectonic events correlate with the excursion between days 42 and 55. Three small earthquakes (M < 2.5) deep beneath Middle Mountain on days 43, 46, and 47 led to C and D level alerts for the first six days of the excursion, but nothing else occurred. The array has never shown any correlation between seismic activity at this scale and significant excursions, so this occurrence is probably coincidence.

Progress has been made in the identification of the noise which has degraded our results for the past two years. After extensive tests, a partial noise source was identified in the 12 bit digitizer and this has been replaced. The digitizer was replaced on day 107 and visible improvements in the data quality are present. The coherencies abruptly improve on this day in Figures 2 through 7 and remain excellent afterwards. The percentage of data passing our cutoff coherency of 0.998 on dipoles 2, 5, and 6 increases after the change (Figures 3, 6, and 7). These dipoles are traditionally our noisiest ones. However, the best data is recorded typically during the summer and we will need a winter to see if the new board is performing well. Our tests also showed that significant improvement can be obtained through use of a 16 bit digitizer, and we have requested funds for one for this next year.

Conclusions

This year has been characterized by a relative absence of activity, even during the most recent seismic events. This lack of precursory signals before the two M4.5+ earthquakes is disturbing but probably indicates that the threshold for measurable electrical changes has not yet been reached in the strain cycle.

Reports Published

Figure 1 - Telluric monitoring array in Parkfield. Electrodes are marked with dots and electronically created dipoles are shown with lines.

Figure 2 - Residual analysis for Dipole 1 for the past 11 months. The first plot is the projection of the residual on the major eigenvector with a scale of +2% to -2% and the second is the projection on the minor eigenvector with a scale of +5% to -5%. Coherencies are between the signal predicted using the telluric coefficients and the measured signals are shown between .998 and 1.000. 95% confidence intervals are shown with dashed line on the projection plots.

Figure 3 - Residual analysis for Dipole 2 for the past 11 months. See caption of Figure 2 for explanation.

Figure 4 - Residual analysis for Dipole 3 for the past 11 months. See caption of Figure 2 for explanation.

Figure 5 - Residual analysis for Dipole 4 for the past 11 months. See caption of Figure 2 for explanation.

Figure 6 - Residual analysis for Dipole 5 for the past 11 months. See caption of Figure 2 for explanation.

Figure 7 - Residual analysis for Dipole 6 for the past 11 months. See caption of Figure 2 for explanation.
Figure 2

DIPOLE 1 SMOOTH= 9

+2%
-2%
+5%
-5%
1.00
.998
193
12293

DIPOLE 1 SMOOTH= 9

+2%
-2%
+5%
-5%
1.00
.998
12393
24493

DIPOLE 1 SMOOTH= 9

+2%
-2%
+5%
-5%
1.00
.998
24593
32793
Figure 3

DIPOLE 2 SMOOTH = 9

+2%

-2%

+5%

-5%

1.00

0.998

12293

DIPOLE 2 SMOOTH = 9

+2%

-2%

+5%

-5%

1.00

0.998

12393

DIPOLE 2 SMOOTH = 9

+2%

-2%

+5%

-5%

1.00

0.998

241493

32793

581
Figure 4

DIPOL3  SMOOTH= 9

-2%
+5%

-5%
1.00
.998
193
12293

DIPOL3  SMOOTH= 9

-2%
+5%

-5%
1.00
.998
12393
24593

DIPOL3  SMOOTH= 9

-2%
+5%

-5%
1.00
.998
24593
32793
Figure 5

DIPOLE 4 SMOOTH = 9

+2%
-2%
+5%
-5%
1.00

193

0.998

12393

DIPOLE 4 SMOOTH = 9

+2%
-2%
+5%
-5%
1.00

12393

0.998

24493

DIPOLE 4 SMOOTH = 9

+2%
-2%
+5%
-5%
1.00

24593

0.998

32793
Figure 6

DIPOLE 5 SMOOTH = 9

+2%  
-2%  
+5%  
-5%  
1.00  

1.000  12293  

1.998  12393  24493  

+2%  
-2%  
+5%  
-5%  
1.00  

1.998  24593  32793  

584
Figure 7
Quaternary Chronostratigraphy and Deformation History, Los Angeles Basin, California

9960-11426, 9960-12426

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Program Element: II

Investigations

1. Geochronology, faunal correlations, and uplift history of the Wilshire arch area, northern Los Angeles basin (9960-11426).

2. Historical re-evaluation of 1906 surface faulting in the southern Santa Cruz Mountains in light of the 1989 Loma Prieta earthquake (9960-12426).

Results

1. In conjunction with Prof. Robert Yeats and his students at Oregon State University, (funded externally through NEHRP), we have been providing stratigraphic and age control to constrain the geometry and slip rate of the Wilshire blind thrust fault, which lies approximately 5 km south of the Santa Monica Mountains (Fig. 1). The Wilshire fault is thought to deform presumed Quaternary-age marine gravels that unconformably overlie dipping Tertiary-age siltstones. We estimate the age of the gravels to be 0.8-1.0 Ma, based on stratigraphic relationships observed in the southwest LA basin, but we have yet to obtain any local age control. We have obtained cores from the underlying siltstones in the Hancock Park area. These cores come from exploratory wells drilled for the Los Angeles MetroRail subway system. Samples from the cores have been analyzed for benthic foraminifera in order to tie this section to existing oil well data and to constrain the maximum age of the deformed gravels. The computed slip rate for the Wilshire fault (2.6-3.3 mm/yr; Schneider and others, 1993) is derived using the 0.8-1.0 Ma estimate; thus, further constraint on the age of these materials bears directly on slip rate determinations.

We assign the siltstones from the MetroRail cores to the Upper Fernando or “Pico” Formation based on their Wheelerian and Venturian benthic foraminiferal assemblages, known elsewhere to be late Pliocene to early Pleistocene in age (~3-1 Ma). However, the provincial early Pliocene to Recent benthic foraminiferal stages (Repettian through Hallian, see Fig. 2) are indicative of a basin-filling cycle and are not based on evolutionary trends. Because their boundaries are known to be time-transgressive, it is desirable to obtain independent age control where possible. The MetroRail cores are particularly significant in this regard because they also contain a suite of at least 10 thin volcanic ash beds, (rarely found in L.A. basin sediments) and diagnostic diatom assemblages. These additional geochronologic markers provide means for verifying age assignments based on foram data from the northern L.A. basin. To date, three of the ten ashes have been correlated to dated tephras elsewhere and suggest an age for the “Pico” of ~4-6 Ma. This age is generally confirmed by the diatoms, which are late Miocene in age and are mostly restricted to the interval between 6.3-6.0 Ma.
Not only is the “Pico” here older than its foram assemblage indicates, but sediments in other parts of the basin that contain younger ashes (~3.4-4.4 Ma) are locally associated with biostratigraphically “older” (Repettian and Delmontian) fauna. The MetroRail data provide a way to quantify the time-transgressive nature of benthic foram stage boundaries and show that they are not, by themselves, reliable age indicators.

These data increase the uncertainty of our age assignment for the deformed marine gravels, and consequently increase the uncertainty of slip rate estimates for the Wilshire fault. However, the implications of these data for the seismic hazard evaluation of blind thrust faults reach far beyond the Wilshire fault. Most recent structural interpretations and models of blind thrusting depend on oil
well data that rely almost exclusively on benthic foraminiferal stages for age and stratigraphic control. Not only are derived fault slip rates based on foram stages potentially more uncertain than we currently recognize, but without other corroborating data, inferred faults and unconformities marked by missing faunal zones and abbreviated stratigraphic section may have little tectonic significance. Even the inferred geometry of subsurface folds could be misinterpreted where the local biostratigraphic stage boundaries diverge widely from geochronologic horizons. As we do not know how localized these problems are, the need for additional independent age control is evident.

Figure 2. Chronostratigraphic framework for the middle Miocene through Pleistocene of California, showing correlation of diatom zones to the benthic foraminiferal stages of the L.A. basin. The MetroRail “Pico” Formation contains benthic foraminifera belonging to the Wheelerian and Venturian stages, but diatoms belonging to the *Nitzchia reinholdii* zone, which falls within the late Miocene. This age is confirmed by tephrochronology. The Nomlaki and Lawlor tuffs, which occur in Repettian and Delmontian sediments on the Palos Verdes peninsula, post-date the ashes found in the Wilshire area. Figure modified from Blake (1991), using the geomagnetic polarity time-scale of Cande and Kent (1992).

2. Historical investigations of the 1906 earthquake in the southern Santa Cruz Mountains allow us to compare effects of the 1906 earthquake to effects of the 1989 earthquake, and provide context for interpreting the nature of coseismic ground deformation in the region. In both 1906 and 1989, many large ground cracks occurred in the Summit Road and Skyland Ridge areas. Three specific localities in the Summit Road area were documented well enough in 1906 to make detailed comparisons with 1989: 1) the Wright’s tunnel, 2) the Morrell Ranch, and 3) the Blacksmith shop at Burrell. Published surveys of Wright’s tunnel indicate a broad zone of deformation extending SW from the San Andreas fault for more than 1.5 km; this survey forms the basis for interpreting the fault zone to be very broad in this region. However, recently discovered documents related to the Wright’s tunnel show that if the tunnel was tectonically offset in 1906, the deformation was distributed over a zone not more than
~100m wide. Left-lateral offset was documented (off the main trace of the San Andreas fault) across two fractures in 1906 near the Morrell ranch, and newly discovered historical documents verify that these are the same two fractures that ruptured with about 50% of the 1906 offset in 1989. The fractures in 1906 were longer and more damaging, but the slip vector orientation was probably identical. Photographs taken in front of the Blacksmith shop at Burrell show that a significant fracture formed there in 1906. Recent research provides the exact location of this fracture and suggests that this rupture may be associated with right-lateral surface faulting within the San Andreas zone. Nothing comparable occurred there in 1989. Virtually no surface rupture occurred along the San Andreas in 1989, whereas careful study of historical documents strongly suggests that throughgoing surface rupture did occur in 1906, although none of the reported values of offset are reliable. Our historical research has added to the understanding of ground rupture in the Loma Prieta region. These studies indicate that fault behavior in 1989 was significantly different from that in 1906, suggesting that the kinematics of the two earthquakes were different. The off-fault ground ruptures were similar in character in both earthquakes but with greater displacements in 1906. These data suggest that the off-fault ruptures are largely independent of fault kinematics and perhaps are produced by strong ground motions.

References


Reports

INVESTIGATIONS:

During FY 1993 we acquired high-resolution seismic reflection data across suspected fault zones in the Los Angeles and New Madrid areas, we purchased 845 km of industry seismic reflection data in the Puget Sound region, and we compiled and reprocessed industry data in the New Madrid area.

RESULTS:

Los Angeles. We were funded to acquire a second phase of high-resolution seismic reflection data within the San Jacinto graben in cooperation with Steve Park of University of California, Riverside, but long-term flooding of the acquisition site prevented data collection. Instead, we used the funds to acquire high-resolution (25 ft source and receiver spacing) seismic reflection data across the Santa Monica fault, in cooperation with James Dolan of the California Institute of Technology. The latter is a project that we were doing background work on at the time we learned that flooding would prevent us from doing the San Jacinto study.

We acquired a single, 4 km long seismic reflection line across the Santa Monica fault beginning at the north end of the Veteran's Administration facility, crossing Santa Monica Blvd., and continuing southward through city streets. We also acquired a very high-resolution line (8 ft source and geophone spacing) adjacent to a trench being dug by James Dolan. The study served as another test of acquiring high-resolution seismic reflection data in urban environments, and involved some of the logistically most difficult data acquisition we have done to date. The object was to cross the Santa Monica fault near the trench, and to look at the near-surface expression of one of the major fold axes overlying the thrust faults in the area. By examining the fold axis in detail, and in particular the deformation of very shallow sediments, we hope to determine ages of folding, relate the trench to the deeper structure, and locate specific features to be trenched or cored in future work. The data, acquired in August, 1993, are currently being processed and interpreted.
New Madrid. We had two components to our New Madrid work in FY 1993. First, we acquired two high-resolution seismic reflection profiles (30 ft source and geophone spacing) across the Benton Hills to determine whether these topographic features are structurally controlled or merely erosional remnants. These data have been processed and forwarded, after our initial interpretation, to personnel in the Missouri Department of Natural Resources for further interpretation. Our preliminary interpretation indicates that there are numerous faults and flexures beneath the Benton Hills, and that most of the faults have a near-vertical attitude. Some of the faults are correlative with surficially mapped faults, which appear to be predominantly right-lateral strike-slip in nature.

A second component of the New Madrid work was to compile and reprocess industry seismic reflection data in the area with the goal of imaging the deep crust and Moho. Analysis of these deep reflection profiles, it is hoped, will provide insights into the processes governing the seismicity in the region, as well as further our understanding of the crustal structure. To date, we have compiled and/or reprocessed 19 of the longest lines distributed throughout the area. During FY 1994 we plan to interpret these data.

Puget Sound. A large part of the year was expended, with Christopher Potter and Samuel Johnson of the Branch of Sedimentary Processes, in dealing with the contracts to purchase 845 km of seismic reflection profiles acquired throughout the Puget Sound region from a geophysical contractor. The data are 5 sec in length, 24-fold, with a 30 m source and receiver spacing. The data arrived during August, 1993 and initial interpretation began immediately.

The preliminary interpretation of these data is that there are numerous fault-bend folds (ramps) that indicate the region is underlain by a decollement with northward motion on the thrust sheet. Balancing the section provides estimates (still being refined) of the depth to the decollement and total horizontal motion on the thrust system. From the interpretation, mean slip rates and predicted locations of previous earthquake deformation are being determined. The latter will be used to direct future studies. The interpretation also provides constraints on the geometry of the Seattle fault: it is interpreted to dip southward at an angle of about 27 degrees, merge with a midcrustal decollement beneath Tacoma, have two splays above it, and have about 10.5 km of thrusting on it. To the north, the Kingston Arch is interpreted to be a ramp anticline formed by about 7.5 km of horizontal motion over a 1.2-km-high ramp in the midcrustal decollement. The interpretation is still in the preliminary stages and is subject to change.

In addition to the seismic reflection work, Meridee Cecil completed preliminary potential field models across the Seattle fault based on earlier interpretations. The results suggest lateral changes in the geometry of the Seattle fault and provide constraints on the density and magnetic properties of rocks at depth. Further work is continuing.
REPORTS PUBLISHED:

Papers:


Pratt, T.L., How old is the New Madrid seismic zone?, Director's Approval 7/2/93.


Williams, R.A., Luzietti, E.A., and Carver, D.L., High-resolution seismic imaging of Quaternary faulting on the Crittenden County fault zone, New Madrid seismic zone, northeastern Arkansas, in internal USGS review.

Williams, R.A., Pratt, T.L., Stephenson, W.J., and Odum, J.K., Seismic surveys for earthquake hazard reduction in the New Madrid seismic zone, northeastern Arkansas, in internal USGS review.

Abstracts:


I. NORTHERN SAN ANDREAS FAULT SYSTEM: PALEOSEISMIC AND SLIP-RATE STUDIES IN NORTHERN CALIFORNIA

II. PALEOSEISMIC INVESTIGATIONS ALONG THE CARIBBEAN-NORTH AMERICAN PLATE BOUNDARY (SEPTENTRIONAL FAULT ZONE), DOMINICAN REPUBLIC

9960-12406, 9960-10406

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NEHRP II.5

Investigations

1) Geological investigations of the San Andreas and related faults in northern California to determine timing of prehistoric earthquakes and average Quaternary slip rates. 2) Historical investigations of the behavior of the San Andreas fault in the Loma Prieta region in 1906. 3) Investigations of the Septentrional fault in the Dominican Republic to determine timing of prehistoric earthquakes and slip rate.

Results

1) Studies of excavations at sites along faults of the San Andreas system in northern California are being pursued to determine timing of prehistoric earthquakes and fault slip rates.

An excavation across the Maacama fault in Talmage, near Ukiah, California, exposed a sequence of marsh, fluvial and lacustrine deposits overlying Pleistocene (?) gravel. The Maacama fault, clearly expressed in the older gravel, has not caused any brittle deformation of the overlying Late Holocene section. The section instead has been folded across the fault zone. Relationships indicate that only one folding event has occurred. Results of new radiocarbon dating show the folding occurred, after about 1670 AD. These data suggest an earthquake large enough to cause surface deformation has occurred on the Maacama fault in the last 300 years.

Sites with high potential for yielding paleoseismic and slip-rate information are being evaluated along the peninsula segment of the San Andreas fault. Preliminary excavations at one site have ruled it out as a candidate for further study. Additional sites are being evaluated.

2) Historical investigations of the 1906 earthquake in the Loma Prieta area allow comparison of the effects of the 1906 earthquake in this region with the effects of the 1989 earthquake. In this region in 1906, as in 1989, many large ground cracks occurred in the Summit Road and Skyland Ridge areas. Three specific localities in the Summit Road area were documented well enough in 1906 to make detailed comparisons with 1989: 1) the Wright's tunnel, 2) the Morrell Ranch, and 3) the Blacksmith shop at Burrell. Interpretation of newly discovered and previously known documents related to the Wright's tunnel show that, contrary to common belief, offset of the tunnel was not distributed over a broad zone. Left-lateral offset was documented (off the main trace of the San Andreas fault) across two fractures in 1906 near the Morrell ranch; newly discovered historical documents verify that these are the same two fractures that ruptured with smaller amounts of left-
lateral offset in 1989. The fractures in 1906 were longer and more damaging. A significant fracture was photographed in front of the Blacksmith shop at Burrell in 1906. Historical research shows the exact location of this fracture and shows that nothing comparable occurred here in 1989. Virtually no surface rupture occurred along the San Andreas in 1989; careful study of historical documents strongly suggests that surface rupture did occur in 1906, though none of the reported values of offset is reliable. This historical research has added to the understanding of 1906 ground rupture in the Loma Prieta region. These studies indicate that fault behavior in 1989 was significantly different than in 1906, but that off-fault ground ruptures were similar, but larger, in 1906.

3. Studies along the Septentrional fault in the Dominican Republic have yielded data constraining the time of the most recent earthquake along the major North American-Caribbean plate-boundary fault. The most recent earthquake occurred between 730 and 830 years ago. The amount of slip produced by this earthquake was determined: about 5m of left-lateral and 2m of vertical slip, suggesting this earthquake was > M7.5. Evidence for earlier earthquakes was collected; the timing of these events will be constrained by the results of radiocarbon dating of samples now in progress. In addition, offsets of about 40m and 55m were measured on stream terrace risers that cross the fault. Radiocarbon dates of the terrace sediments, now in progress, will allow estimation of the slip rate of the Septentrional fault.

Reports


Analysis of Crustal Deformation Along the Southernmost Segment of the San Andreas Fault System, Imperial Valley, California: Implications for Earthquake Prediction

Program Element II.3

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INVESTIGATIONS

This project involves using geodetic observations in conjunction with other geophysical and geological information to investigate active tectonic processes along the southernmost segment of the San Andreas fault system. Our primary efforts during the present contract period include:

1. Completing a multi-institutional Global Positioning System (GPS) campaign along an approximately 450 km section of the Pacific-North America plate boundary from east of Los Angeles, California to the Gulf of California, northern Mexico.

2. Continuing analysis and interpretation of 1986 to 1993 GPS measurements in the Imperial Valley-Salton Trough with emphasis on temporal and spatial patterns of regional strain accumulation, strain release associated with major earthquakes, and active tectonics of the complex transition from ocean spreading in the Gulf of California to continental transform faulting along the San Andreas fault system.

RESULTS

1. From 15 - 28 February 1993 a GPS campaign was carried out along an approximately 450 km segment of the Pacific-North American plate boundary from the “big bend” section of the San Andreas fault south to the northern part of the Gulf of California in Northern Baja/Sonora, Mexico. The network extends from the Pacific Ocean to the California-Arizona border, a distance of roughly 300 km (Figure 1). Most stations in the network were observed with GPS during previous Salton Trough Riverside County (STRC) campaigns in 1988, 1989, 1990, and 1991. A total of 16 receivers were fielded. In addition, the PGGA stations at Scripps and Pinyon Flat, and the U.S. Army station at Yuma were observed in coordination with this campaign. All instruments were Trimble 4000SSTs and SSEs (identical antennas). A total of 57 stations were observed, most for a minimum of 3 days. Observations were
made each day at 6 stations in the network (Figure 1). The observations were designed to facilitate integration with recent GPS campaigns organized by the Southern California Earthquake Center (SCEC) following the Joshua Tree-Landers-Big Bear earthquakes, and by NGS in the Imperial Valley. In addition, observations in Northern Mexico compliment and extend coverage for the NASA/DOSE Northern Baja, California survey completed during April 1993. A complete set of the GPS observations have been archived at the University Navstar Consortium (UNAVCO).

Participants in the GPS field campaign included Lamont-Doherty Earth Observatory (L-DEO), Riverside County Flood Control and Water Conservation District (RCFCWCD), Centro de Investigacion Cientifica y de Educacion Superior de Ensenada (CICESE), Lawrence Livermore National laboratory, Scripps IGPP, and the U.S. Army (Yuma) Optical Development and Integration Branch. Both the US and Mexico field work were fully supported by UNAVCO.

2. We continue to concentrate on reduction, analysis, and interpretation of the 1986-1993 GPS observations in collaboration with USGS (Pasadena), L-DEO, NGS, SCEC, and CICESE. Crustal deformations derived from the 1986-1990 observations have been used to investigate coseismic deformation for the 1987 Superstition Hills earthquake (Larsen et al., 1992), regional strain accumulation (Larsen and Reilinger, 1992), and active tectonic processes in the complex transition zone from spreading in the Gulf of California to continental transform faulting along the San Andreas fault (Reilinger and Larsen, 1993).

GPS observations for the period 1990-1992 are being used in conjunction with USGS EDM measurements to investigate the slip distribution of the 23 April 1992, M=6.1 Joshua Tree earthquake (Bennett et al., 1993). Measurements at 19 sites (6-GPS 13 EDM) before and after the event have been corrected for secular deformation in order to estimate coseismic movements. The coseismic motions are used to invert for fault slip with the strike, dip and location of the fault determined by the earthquake and aftershock locations. The resulting slip distribution is shown in Figure 2B and the comparison between observed and calculated motions in Figure 2A. Our results suggest a moment of $1.7 \times 10^{25}$ dyne-cm, generally consistent with seismic estimates. The slip distribution is consistent with the hypocentral location, seismic evidence for unilateral rupture to the north, and correlates remarkably well with the aftershocks; most aftershocks occurring where the main shock caused large stress increases. Using the largest aftershock as an empirical Green’s function, we also estimate the relative source time function from which we obtain a rupture duration of 5 sec consistent with the approximately 12-15 km rupture diameter. We are currently investigating the implications of these results for stress changes on nearby faults and at the hypocenter of the Landers main shock.

**PUBLICATIONS**


Figure 1. GPS stations observed during the 1993 Salton Trough-Riverside County/Northern Baja California campaign. Large dots show sites occupied throughout the survey.
Figure 2. A) Observed (with 1 sigma error ellipses) and modeled static surface deformation for slip distribution shown in Figure 2B. Capitalized sites are GPS, others are EDM. B) Modeled slip distribution for the M=6.1, 23 April 1992 Joshua Tree earthquake. Solid diamonds are main shock and foreshock hypocenters, open diamonds are aftershocks. Earthquake hypocenters courtesy of Egill Hauksson.
FLUID PRESSURE AND EARTHQUAKE GENERATION

9960-10216, 9960-11216, 9960-12216

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Program Element II
Investigations

1. The project carried out real-time monitoring and processing of water level data from two areas of California: Parkfield, and the Mojave Desert. Water level data were processed in real time to remove tidal and barometric fluctuations, and the processed data were automatically screened for anomalous signals.

2. Water level measurements were made in two wells in the east San Francisco Bay area in order to determine whether these wells would be suitable for long-term monitoring.

3. Finite element calculations were made of stresses and pore pressure beneath an axisymmetric reservoir impounded on a porous elastic half space in order to investigate the mechanism of reservoir-induced seismicity.

Results

Parkfield Water Levels

In cooperation with the USGS Water Resources Division, water level data from a network of 11 sites near Parkfield, California, were collected throughout the reporting period. Site locations are shown in Figure 1. Raw water level, barometric pressure, and rainfall data are shown in Figures 2a-d.

Water levels in many wells rose beginning in January due to seasonal recharge. In the Middle Mountain (MM) well near Parkfield, water level changes associated with fault creep on the San Andreas fault continue to be observed, as they have been at this site since recording there began in 1987 (Roeloffs et al., 1989). No other signals due to fault motion were identified in the Parkfield water level data during FY93.

Mojave Water Levels

Water level data recording was resumed in the Hi Vista and Crystallaire wells. The well locations are shown in Figure 3 and the data are shown in Figure 4. Water level in the Crystallaire well rose beginning in February, presumably in response to seasonal recharge. A smaller water level rise took place in the Hi Vista well beginning in late August. This rise may be due to recharge, which would be expected to occur later in the Hi Vista well because of its greater distance from elevated recharge areas. Data quality from both wells continues to be good.
East Bay Water Levels

Two locations with existing well bores were instrumented using on-site data loggers in the East Bay. Site locations are shown in Figure 5. The filled diamonds show the water level site locations, the open diamonds show three creepmeter locations and the crosses show the location of two borehole volumetric strainmeters.

There are three adjacent well bores at the site denoted by CMY in Figure 5. Water level data collected from the shallow(p1), middle(p2) and deep(p3) boreholes are shown in Figure 6. The three large water level rises in the shallow borehole are believed to be caused by interruption of pumping in a nearby well. Small offsets in the water level data from the middle borehole can be seen during the transient episodes logged in the shallow borehole. In the deepest borehole, water level transients lasting from one to several days were recorded, but do not correlate with earth tides, barometric pressure, or the pumping transients observed in the shallow well. Because none of the water level data from these three boreholes displays a response to earth tides or barometric pressure changes and because of the interference from pumping in the upper two intervals, no further monitoring at this site is planned.

Water level data is currently being recorded at the site denoted by HPD in Figure 5.

3-D Coupled Stresses and Fluid Flow

The project is using finite elements to calculate coupled stress and pore pressure fields beneath reservoirs. These calculations are a basis for evaluating changes in the Coulomb failure function caused by reservoir impoundment, for comparison with observations of reservoir-induced seismicity. A key FY93 objective was to extend the work of Roeloffs (JGR, 93, 2107-2124, 1988) for two-dimensional reservoirs in plane strain to axisymmetric geometry. For many reservoirs, the axisymmetric calculations will give a better estimate of the rate at which induced stresses and pore pressure fall off with distance from or depth below the reservoir.

Axisymmetric finite element calculations have been made of stresses and fluid pressures under a circular reservoir. The calculations were made at Northwestern University using the ABAQUS finite element program, and embody full coupling between deformation and fluid flow. Results include the rate at which pressure changes fall off with depth beneath the reservoir and simulated pore pressure changes associated with realistic reservoir level histories. The results will be post-processed to resolve the stresses onto planes and evaluate the expected change in fault stability.

Figure 7 shows the axisymmetric finite element mesh, and Figure 8 shows synthetic time histories of water levels in observation wells for the reservoir level history of Bad Creek pumped storage facility in South Carolina. The synthetic water level curves can be compared with data to constrain values of the poroelastic constants and the diffusivity. Both the two-dimensional and axisymmetric solutions predict that reservoir impoundment will change stress and pore pressure by at most several tenths of a bar at hypocentral locations.
Reports:


Figure 1. Map showing water wells near Parkfield California, monitored as part of the Parkfield Earthquake Prediction Experiment.
Figure 2. (a) Water level, barometric pressure, and rainfall records from Parkfield, California. Hourly values are plotted for water level and barometric pressure. Water level is in centimeters above an arbitrary datum. Barometric pressure is in centimeters of water with respect to an arbitrary datum. Bars indicate total rainfall in a 24 hour period. Site names are indicated at right. Julian day number is given on top axis.
Figure 2. (b) Water level records from Parkfield, California plotted as in Figure 2(a).
Figure 2. (c) Water level records from Parkfield, California plotted as in Figure 2(a).
Figure 2. (d) Water level records from Parkfield, California plotted as in Figure 2(a).
Figure 3. Map showing water wells in southern California in which water level is monitored.
Figure 4. Water level records from southern California plotted as in Figure 2(a).
Figure 5. Map showing water wells (HPD, CMY) in the east San Francisco Bay area in which water levels have been monitored. Creepmeters (HWR, HWD, HWP) and borehole strainmeters (CUL, GAR) are also shown.
Figure 6. Water level records from the east San Francisco Bay area plotted as in Figure 2(a).
Figure 7. Axisymmetric finite element mesh used for calculating stress and pore pressure fields beneath a round reservoir. This simple geometry is equally applicable to many reservoirs, but for illustration purposes can be taken to represent Bad Creek reservoir in South Carolina. OW3 indicates the position of a monitoring well near Bad Creek Reservoir.
Figure 8. Time histories of reservoir level and pore pressure calculated using a fully coupled finite element program (ABAQUS). This example is tailored to the Bad Creek reservoir in South Carolina; the solid curve shows the pond elevation at Bad Creek. Calculated pore pressure is shown for two sets of material properties at the bottom of the observation well in Figure 7. The values of Skempton’s coefficient, $B$, and diffusivity, $c$, are labeled on the curves. Actual data from OW3 more closely resemble the upper dashed curve, suggesting either that Skempton’s coefficient and/or hydraulic diffusivity are relatively high for Bad Creek.
Objectives

The objectives of this project have been to:

1) adapt a two step moment tensor inversion technique for surface waves originally developed and applied in the global and large scale regional context, to the case of short periods and regional distances relevant to studies in California.

2) to implement this technique together with a near field moment tensor technique, on a routine basis, in order to complement the northern California catalog with systematic estimates of seismic moment and source parameters for events of magnitude larger than 4, and to take the first steps towards uniformisation of the Berkeley and USGS northern California earthquake catalogs.

Results

The Seismographic Station at the University of California at Berkeley has traditionally determined locations and magnitudes of earthquakes of magnitude larger than 2.5 in the Bay Area and of magnitude larger than 3.0 in most of central and northern California. These magnitudes were, until January 15, 1993, determined from the readings of Wood-Anderson torsion seismographs at 4 locations (BKS, MHC, ARC, MIN) and this procedure has been followed since the time of installation of these instruments in the 1930's, leading to the production of a very uniform catalog of earthquakes for northern and central California.

The current Berkeley Catalog also contains epicentral locations based, until recently, on data from 19 short period stations located in central and northern California. These locations are sometimes different from those obtained by USGS/Menlo Park, and based on readings from the Northern California Network (NCN), as are the magnitudes obtained from this network using coda
wave data. A uniformisation of these catalogs is clearly needed. Jointly with colleagues at Menlo Park, we have begun to investigate different options for establishing a parameteric database that would effectively merge complementary information from NCN and Berkeley.

As of January 15, the Berkeley Seismographic Station has ceased to collect photographic records from Wood-Anderson instruments at stations BKS, MHC and ARC. The estimates of local magnitude ($M_L$) are now obtained by synthesizing the response of the Wood-Anderson instruments from broadband records at the same sites. This response has been carefully calibrated over the past year by 1) considering the nominal Wood-Anderson response as obtained from earlier calibrations (Uhrhammer and Collins, 1989) and 2) adjusting the amplitude level of the response by comparing maximum amplitude readings on photographic paper with those obtained digitally from the broadband instruments (Anderson et al., 1993). The last operational Wood Anderson instruments are kept running at station MIN, which was upgraded to broadband instrumentation in March 1993, until the end of 1993.

The new "synthetic" estimation procedure for $M_L$ allows to both retain continuity with the historical Berkeley catalog, and to introduce modern practice: robust estimates can now be obtained in close to realtime using data at all available broadband sites.

However, $M_L$ is not the best estimator of the size of an earthquake and the availability of broadband digital data is an opportunity to develop routine estimation of moment tensor and moment magnitude ($M_w$). Indeed, the Berkeley Seismographic Station is renovating its central and northern California network to upgrade and expand the BDSN (Berkeley Digital Seismic Network) established in 1986, an initially heterogeneous broadband network consisting of 3 sets of STS-1 instruments (ORV, MHC, SAO), one set of Guralp CMG-3 (CMB), one set of IULP Sprengnether S-5100 (BKS), and a vertical Sprengnether S-5100 (free period = 40 sec, WDC). These stations have been upgraded to Very Broad Band STS-1 or STS-2 three component seismometers, FBA-23 strong motion accelerometers, and 24 bit Quanterra recording systems, linked to the UCB Campus headquarters in McCone Hall through continuous telemetry (by means of phone and microwave circuits). Eleven stations are operational since August 1993, and 5 are in the process of installation. Figure (1) shows the location of the existing and planned stations.

Moment tensor determination using surface waves

Robust methods, based on low frequency surface wave data, have been developed for some time now to determine moment, source mechanism, depth and source duration of earthquakes large enough to be observed worldwide (e.g. Dziewonski et al., 1981; Kanamori and Given, 1981; Romanowicz and Guillemant, 1984). These and other "global" techniques are becoming increasingly efficient, and, in fact, are now accessible to be performed by practically any...
group of seismologists through the establishment of rapid data collection systems such as Gopher, Badger and other dial-up systems.

The idea of using fundamental mode surface waves to determine moment tensor of shallow earthquakes at regional distances (100-1000 km) has the following advantages:

1) the inverse problem is linear in the moment tensor elements and does not require a starting solution.

2) the theory is well established and its application has been demonstrated to work well in the teleseismic case, both at very low frequencies (Kanamori and Given, 1981; Romanowicz and Guillemant, 1984; Zhang and Lay, 1989) and in the frequency range 20-100 sec, when path calibrations for the phase are available (e.g. Patton, 1979; Romanowicz, 1982; Patton and Zandt, 1991).

3) A similar approach has recently been shown to work with TERRAscope data in southern California (Thio and Kanamori, 1991).

When accurate path corrections are available, the equations, linear in moment tensor, are solved typically by sampling data at a number of stations and a number of frequencies in an appropriate frequency band, successively at a number of trial depths. The solution is found by minimizing the residual, in a least squares sense, to the system of equations.

When a two-step procedure which takes advantage of the known azimuthal signature of the source radiation pattern is used, as proposed by Romanowicz (1982), an approximate model for propagation corrections is sufficient to obtain robust and accurate moment tensor solutions, when a good azimuthal distribution of stations is available. In the global case, and for large earthquakes which generate well dispersed low frequency fundamental mode surface waves in the period range 160-300 sec, a spherically symmetric reference earth model for propagation corrections is generally sufficient. For smaller earthquakes, the period range has to be shifted to shorter periods, and path calibration is necessary. Typical successful applications concern the period range 20-100 sec, at teleseismic distances, and path calibration is performed using reference events, for which the mechanism and depth are independently known.

The adaptation to shorter distances (100-400 km) and smaller earthquakes (magnitude >3.5) requires:

1) a regional model for the calculation of eigenfunctions and the resolution of the uncertainty in number of cycles for the path corrections in phase

2) an appropriate choice of the frequency range and group velocity window, which depends on epicentral distance, in order to avoid contamination by other phases

3) refinement of the path corrections through systematic path calibrations.

For the past year, we have been systematically estimating moment tensor and depth of earthquakes in central and northern California using the two-step moment tensor inversion procedure described above and adapted to the period range 15-60 sec and distance rage 100-500 km, allowing us to use data from the
BDSN, and occasionally TERRAscope. We have developed a suitable model for propagation corrections in this region. The solutions are systematically compared to those obtained from bodywaveform modeling (Dreger, 1993), and, whenever possible, near-field moment tensor inversion as described below.

The solutions are complete down to magnitude 4. The solutions obtained for the time period July 1992-July 1993 are shown in Figure 2, and listed in Table I, where they are compared to solutions obtained by the two other methods. The comparison of results using different methods allows us to estimate the level of confidence in our solutions. Mechanisms agree, in general, to within 10° for each plane orientation, and estimates of moment-magnitude to within 0.3 units of magnitude. Improvement of path calibrations should reduce the scatter in magnitude, in the future, to less than 0.1 unit in magnitude.

Detailed path calibration is proceeding as earthquakes occur in different parts of the State. Figure 3 shows an example of improvement of the fit to the phase of Love waves for the Parkfield earthquake of 04/04/93, when a regionalized model for California is used. This model consists of three regions: "Central Valley", "Coastal Ranges" and "Southern California". The moment obtained after path regionalization is also more consistent with the magnitude estimate from the NCN (A. Michael, personal communication).

**Near field single station moment tensors**

For the smallest events, signal to noise ratio is not always sufficient at more than one closest station. For this case, we have developed a single station near-field moment tensor inversion method (Uhrhammer, 1993), which takes advantage of the near-field source terms. These produce ramps between the P and S waves on all three components and the intermediate field source terms produce step offsets at the P and S onset times. An example of ground displacement seismogram which exhibits these ramps and offsets in the MHC broadband recording of a small earthquake which occurred on 08/28/88 along the Calaveras fault zone, is given in Figure 4. At local distances, the far-field approximation does not hold and most of the energy in the seismogram is at relatively high frequency. A useful and robust approach is to invert for the moment tensor components using a least-squares scheme in the time domain. The synthetic seismograms are calculated using a half-space model, which is sufficient for modeling the near and intermediate field terms. Figure (4) shows the fit to the data obtained by inversion of the 08/28/88 event data as well as the retrieved mechanism and moment. These estimates are compare to the USGS/Menlo Park first motion solution (Oppenheimer, personal communication).

The recent events in the vicinity of Parkfield provide an opportunity to illustrate the usefulness of this approach. Figure (5a) shows the mechanisms obtained by R. Uhrhammer for 4 events ranging in magnitude from 3.0 to 4.0 that occurred at distances less than 15 km from the BDSN station at Parkfield (PKD). Figure 5b shows the fit to the data for the largest event.
The large dynamic range and wide bandwidth of the very-broadband seismometers produce useful near-field seismograms for magnitudes greater than 2, which can be used to complement the surface wave and body wave inversions. For larger events, this approach provides an independent check on the results obtained using other methods. For events of magnitude smaller than 3, other modeling approaches begin to fail due to small signal-to-noise ratios at larger distances.

This multi-method approach allows us to obtain reliable moment tensor solutions for events as small as magnitude 2 to 2.5 and as large as magnitude 6 and larger. These are now routinely determined at the Seismographic Station and archived in the Berkeley catalog, which is available on line from the joint UCB/USGS northern California Data Center. Moreover, for all events of magnitude 4 and larger, these solutions are obtained rapidly (within minutes or hours, depending on the circumstances) following the occurrence of the earthquake (Romanowicz et al., 1992), and the solutions dispatched by e-mail to interested institutions.

References


Thio, H.K. and H. Kanamori (1991) A surface wave study on the structure of the crust and upper mantle under southern California, EOS, 72, 324.


Publications and oral presentations under this funding


Table I. Source parameters for events from July 1992 - June 1993. Epicentral coordinate information from the UCB/USGS Seismic Data Center. Asterix indicates the solution plotted in figure 2. Key to methods: (1) Regional surface wave inversion, (2) Regional body waveform inversion, (3) Single station near-field inversion.

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<th>Lon. (°W)</th>
<th>Depth (km)</th>
<th>$M_L$</th>
<th>$M_w$</th>
<th>$M_o$  (N-m)</th>
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Figure 1: Existing (full squares) and planned (shaded squares) broadband stations telemetered continuously to the BSS Station STAN is contributed by Stanford University. Insert: Existing and planned stations for the Northern Hayward Fault Network. Triangles represent the Southern Hayward Fault Network deployed by the U.S. Geological Survey.
Moment Tensor Solutions (July 1992 - June 1993)

Figure 2: Source mechanisms obtained for the time period from July 1992 to June 1993. These mechanisms represent the best double couple fits to the moment tensors obtained by surface wave inversion and are scaled to the value of the seismic scalar moment. The locations of the BDSN and TERRAscope networks are given (squares).
Figure 4: Comparison of observed (dashed) and synthetic (solid) waveforms for near-field displacement recorded at MHC for a small (ML=2.9) earthquake which occurred along the Calaveras fault (depth = 8.1 km; distance = 16.0 km, azimuth = 5°). Left: results of unconstrained time domain moment tensor inversion. The inset mechanism is the best fitting double-couple solution. The uncertainties on the strike, rake and dip of the best fitting double-couple are on the order of 0.1 rd. The fit to the near-field components is very good. Right: synthetics computed for the focal mechanism inferred from the USGS first motion data. Note that the near-field components do not match well with the observations. This in not surprising when one considers that the uncertainty in the strike, rake and dip for this solution is of the order of 0.3 to 0.7 rd, and that the near-field components are very sensitive to the orientation of the focal mechanism.
Figure 3: Left: Comparison of the fits to the source phase at a period of 32 sec (Love waves) using a) a standard western US model for all stations, b) regionalized propagation corrections using three different regions in California: coast ranges, Great Valley, and southern California (Figure 6). Station MLA, which has the most "mixed" path with a portion in the Sierra Nevada, remains poorly modelled. Right: corresponding source mechanism (solid line) and moment, compared to body waveform modelling solution (Dreger, personal communication). The slightly higher Mw obtained in b) is in better agreement with the USGS/Menlo Park magnitude.
Near-Field Analysis of 1993 Parkfield Sequence

Near-field Moment Tensor Solution

PKD1930940521

\[ Mo = 1.3 \times 10^{23} \text{ dyne-cm} \]
\[ M_w = 4.7 \]
\[ \text{RMS Correlation} = 0.923 \]
\[ \Delta = 10.0 \text{ km} \& \text{Az} = 140 \]
\[ \text{Depth} = 7.8 \text{ km} \& \text{Duration} = 1.08 \text{ sec} \]

P1: Strike, Rake & Dip = 35, 8 & 86

P2: Strike, Rake & Dip = 305, 176 & 82

Figure 5: The map shows the locations and focal mechanisms for four earthquakes which occurred along the San Andreas Fault near Parkfield between February 15 and April 8, 1993. Details of the near-field moment tensor solution for the largest earthquake is shown on the right. The ground displacements recorded by the BDSN station PKD are shown as solid lines for the vertical (Z), radial (R) and transverse (T) components. The corresponding synthetic waveforms for a half-space velocity model are shown as dashed lines. The low-frequency features in the observed waveforms, which are well matched by the synthetics, provide the information about the moment tensor of the earthquake. The focal mechanism plot (ball) on the right indicates the compressional (shaded) and dilatational (unshaded) quadrants of the earthquake source.
LATE QUATERNARY FAULTING, SOUTHERN SAN ANDREAS FAULT

9960-11346

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Investigations

1. Continued study and mapping of active faults and adjacent geology in the Coachella Valley and Little San Bernardino Mountains.

Results

1. Geologic mapping (with Judi Sheridan, Univ. of Oregon) of the San Andreas fault zone in the Mecca quadrangle in the Mecca Hills is about 80% complete. Mapping at 1:12,000 and 1:16,000 scales reveals new complexities in the San Andreas and associated faults in the Mecca quadrangle. One of the more interesting details is that the Skeleton Canyon fault, which was previously mapped on both sides of Painted Canyon is now believed to be two faults, which are quite distinct, both in their structural style of faulting and in their trends. The Skeleton Canyon fault proper (the one that passes through Skeleton Canyon) dips to the northeast, is en echelon to the San Andreas, and at its northern end is within about 200 m of the San Andreas fault; in contrast, the fault northwest of Painted Canyon is nearly vertical, contains a 0.5 to 6-m-thick intruded clay layer, is about 600-700 m from the San Andreas throughout its length, and rolls over into bedding at its southern end.

2. In March, 1993, new locations of fault slip were found along the San Andreas fault in the central Mecca Hills. [Field investigations of possible triggered slip immediately following the 1992 Landers earthquake missed this area because of rock falls blocking the only driveable stream channel.] The area of new observations showed slightly rounded right-lateral surface slips of 1 1/2 to 2 cm. Surface slips associated with the Landers earthquake formed both to the northwest and southeast of this area. This area is where earlier triggered slips, associated with the 1968 Borrego Mountain and 1979 Imperial Valley earthquakes, were near their maximum. Cumulative amounts of triggered slip in the central Mecca Hills
from 1968 to 1992 amounts to about one fourth the geodetically estimated slip rate for this stretch of the San Andreas fault.

3. Three potential trenching sites have been found across active faults in the Little San Bernardino Mountains. The three sites are on the Eureka Peak, East Wide Canyon, and Long Canyon faults. The Eureka Peak fault slipped at the ground surface in association with the 1992 Landers earthquake (about 21 cm at the trench site), and the East Wide Canyon fault slipped sympathetically in association with the 1992 Joshua Tree earthquake; no surface slips have yet been documented on the Long Canyon fault. All three trench sites are in Quaternary material that should provide a significantly improved understanding of the prehistoric record on these three faults.

4) More faults have been mapped northeast of the San Andreas fault in the Indio Hills. An extensive set of faults was mapped there by Clark (1984); the newly located faults extend the coverage of densely faulted area farther north, toward the Little San Bernardino Mountains. These faults are splays off the San Andreas fault. The newly mapped faults cut Quaternary alluvial fan deposits and some trend toward seismically active faults in the Little San Bernardino Mountains. The newly mapped splay faults, therefore, may be conduits for slip partitioned off the San Andreas that passes through the Little San Bernardino Mountains and then farther northward into the eastern California shear zone, the site of the 1992 Landers earthquake.

Reports published

Objectives

The purpose of this research is to understand the mechanical relationship between fault zone deformation, as measured using paleomagnetic rotations, and fault slip. One of the integral questions associated with this problem is the grain-scale deformation of the rock or sediment.

Results Obtained

We excavated two parallel trenches across the San Andreas fault near San Andreas Dam in San Mateo County, California. These two trenches cross a sag pond in a right-step in the fault and bracket a fence with measured offset in the 1906 San Francisco earthquake. The trench exposed massive gravely clay in the center of the sag pond with clayey-gravel colluvium interfingerling from the hillslope to the east and Franciscan "bedrock" exposed in the west end of the trenches. Trench logs (Figure 1) show four styles of deformation, and possibly a fifth. The most pronounced zone is a 0.75 m wide zone of mixed clays with anastomosing and lenticular clay bodies. There is no evidence of a single planar trace within this zone and the zone aligns with the mapped offset from 1906. Interestingly, the projection of the zones between the two parallel trenches does not coincide suggesting a small (0.5 m) right-step between the trenches.

The second style of deformation was fissuring, some with small vertical separations (a few centimeters) in the gravel colluvium in the eastern end of the trenches. It is not clear if the majority of these represent tectonic offsets or just ground cracking in earthquakes without tectonic offset.

A third style of deformation was the distributed deformation between the pronounced fault zone and the western end of the trenches. This deformation penetrated the "bedrock" exposed in the trench and could be correlated with offsets in the bedrock surface and small possible scarplets on the ground surface. In the sediments underlying the clay, the distributed deformation is seen as mixing of the gritty colluvium with vertical zones of clay interpreted as planes of concentrated shearing.

The fourth style of deformation is seen in a zone in the middle of the north trench. The gravelly colluvial layers are disrupted and fissures are seen penetrating downward into the clay. This disruption does not affect the underlying tan-brown sandy clay. However the sandy clay does show the fifth, and least understood, feature. The sand contains vertical veins filled with dark clay similar to that overlying it. The origin of these veins is not understood and they may be unrelated to tectonic deformation. Although unlikely based upon the very fine grained nature of the sediments, liquefaction cannot be ruled out. The association with the overlying disruption would tend to support this. It is also not understood if the clay filling comes from the overlying clay or a lower unit not exposed in the trench.
About three hundred and fifty samples were collected for paleomagnetic analysis. Samples were collected from four of the five styles of deformation; the gravels with the fissuring at the east end of the trenches were not suitable for paleomagnetic analysis. Preliminary results for the susceptibility and anisotropy of magnetic susceptibility (AMS) are shown in Figure 2. There is a marked increase in the susceptibility of the clay within the zone of mixed clay. There is an accompanying increase in the scatter between neighboring samples but within this scatter there is a suggestion of a lower susceptibility region in the center of the zone with higher susceptibility at the edges. There is no apparent increase in the anisotropy of the samples as a group, but again the scatter of the values increases within the zone of mixed clays. Certainty on these number will increase as additional duplicate samples are measured.

Detailed analysis is still required to distinguish this as a tectonic effect from the fault motion or a sedimentological effect of mixing three or four types of clay.

Effort has also been put into improving the analysis of paleomagnetic, susceptibility, and AMS data. Modifications have been made to the software that runs the susceptibility bridge measuring unit to improve its portability, provide better error checking, produce more informative output, and preserve the raw measurements. Now, using the raw measurements as input, software has been written, and is being continually upgraded, to provide better analysis of the data including a full least-squares inversion of the data for the susceptibility tensor and a bootstrap analysis of the data for the confidence limits on the parameters.
Fence posts

1 meter (no vertical exaggeration)

- black slightly-gravelly clay
- gravel/clay colluvium
- zone of mixed clay (fault zone)
- tan-brown sandy clay
- light-brown clayey sand with Franciscan clasts
- "bedrock(?)" - Sheared Franciscan rock

**Figure 1:** Generalized log of the south wall of the north trench across the sag pond near San Andreas Dam. Fence posts offset in the 1906 San Francisco earthquake are projected onto the log. Fissures are shown as wavy lines cutting the colluvium and black clay and the line of paleomagnetic samples shown in Figure 2 is shown by the horizontal line across the zone of mixed clay. Contacts are dashed where gradational.
Magnetic Properties Across the Primary Fault Zone
North Trench, South Wall

Figure 2: Magnetic susceptibility (circles) and percent magnetic anisotropy (triangles) of samples collected across the zone of mixed clay which is interpreted to be the primary fault zone exposed in the trenches. The right side of the plot is the western edge of the zone. An increase in the scatter of both properties is seen within the fault zone with a significant increase in the susceptibility of the clay, particularly along the edges of the fault zone. It has not yet been determined if this is purely a tectonic effect or if mixing of different clay units are also important.
Program Element II

Quaternary Tephrochronology in the Western Region in Support of Earthquake Hazards Reduction Studies

9540-70020; (1993)

Tephrochronology Project (of the Western Region, Menlo Park)
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Investigations

The Tephrochronology project provides stratigraphic correlation and age control to studies of active faults and neotectonics in the Western Region by means of chemical analysis and numerical age dating of tephra (volcanic ash and tuff layers). New studies or ongoing studies are with:

1. Michael Rymer (BESG, Menlo) on the geologic structure, transpression, and neotectonics of the San Andreas Fault in the Salton Trough, California, using the Bishop ash bed and other tephra layers as chronostratigraphic markers.
2. Marith Reheis (BCRG, Denver) on Neogene displacement of the Fish Lake Valley Fault Zone, the northern extension of the Furnace Creek Fault Zone in eastern California and western Nevada, and late Neogene tectonics of Fish Lake Valley.
3. Richard Madole and Robert Schuster (GRA, Denver), on the age and paleoseismic significance of the Ribbon Cliff landslide of the Columbia River, central Washington, as it relates to the location of the epicenter of the North Cascade earthquake of December 14, 1872.
4. Earl Brabb (BWRG, Menlo) and Davey Jones (Univ. of Calif., Berkeley), on the age and correlation of early Neogene tephra layers, for age control in tectonic and chronostratigraphic studies of the eastern San Francisco Bay area.
5. Robert Fleck (BIG) and Malcolm Pringle (formerly of BIG, Menlo) on laser-fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating of late Neogene tephra layers as chronostratigraphic horizons in the western U.S.
6. Dan Ponti (BESG) on potential problems in evaluating activity on blind thrust faults using benthic foram biostratigraphy in the northern Los Angeles basin.
7. Ray Weldon and students (Univ. of Oregon) on tephro-chronologic age constrains for neotectonic displacements in the Summer Lake area, southeastern Oregon.
8. Anna Buising and Dean Richesin (Cal State, Hayward) and Alan Bartow (BWRG, Menlo) on age constraints on deformed upper Cenozoic strata, east-central Coast Ranges, Calif.
9. Jim Yount (BWRG, Carson City) and Dave Harwood (BWRG, Menlo) on upper Quaternary stratigraphy and deformation of Mohawk Valley, northeastern Calif.
10. Emilio Herrero-Bervera, Chuck Helsley (SOEST-Univ. of Hawaii), Robert Negrini (Cal. State, Bakersfield), Mike McWilliams (Stanford Univ.), Brent Turrin (BWBR, Menlo), Julie Donnelly-Nolan (BIGP, Menlo), and others on the age, correlation, and identity of a paleomagnetic episode in the Brunhes Normal Chron.
Program Element II

Results (refer to corresponding numbers, above)

1. (a). New tephrochronologic and biostratigraphic evidence from Garnet Hill, at the northwestern end of the Salton Trough, indicates that the trough was open to fluvial and then marine deposition as early as late Miocene time. Age control on the marine beds are from tephrochronology and diatom biostratigraphy. (b). Report on mid-Quaternary faulting and deformation along the southern San Andreas Fault in the Mecca and Indio Hills, using the Bishop ash bed as a chronostratigraphic marker, is close to completion (Rymer).

2. Neogene and Quaternary tephra layers have been collected from Deep Springs Valley, east-central Calif., and are being analyzed in order to provide information on the neotectonics of this area, the site of a recent M ~6 earthquake.

3. A report on the Ribbon Cliff, Wash., landslide is now complete and has been through review. This report documents the timing of landsliding and shows that the slide is a polygenetic landform that has moved at least twice before the 1872 earthquake.

5. Two reports on new laser-fusion ⁴⁰Ar/³⁹Ar ages, one on the Bishop ash bed and the other on the Tuff of Taylor Canyon, are nearly complete. These are two widespread late Neogene tephra layers in the western U.S. The Bishop ash bed and tuff were erupted from the Long Valley caldera east of the central Sierra Nevada, the Tuff of Taylor Canyon, a complex of several tuffs, was erupted from the Glass Mountain area, just east of Long Valley.

   The new age for the Bishop ash bed, 0.758 ±0.002 Ma, is based on about 80 individual determinations of individual sanidine crystals or groups of a few small crystals, and is precise (±0.3%). This result provides a new constraint on the Brunhes/Matuyama Chron boundary of 0.775 ±0.005 Ma, in reasonable agreement with recent data reported from other areas.

6. Cores drilled for the Los Angeles MetroRail subway system along Wilshire Blvd. encountered dipping sandstones (part of a fold related to a detachment fault at depth?) estimated to be ~0.7 to 2.5 Ma, based on benthic foraminifers, but 4.4 to 6.0 Ma based on two independent lines of evidence from tephra and diatom assemblages. These finding have important implications for interpretations of the rates of subsurface deformation, such as blind thrusts and detachment faults and folds in this region.

8. Identification of the Lawlor Tuff (4.1 ±0.2 Ma) in steeply-dipping Miocene to Pliocene strata at the western margin of the San Joaquin Valley near Patterson, together with a Hemphillian horse tooth, provide evidence for late Cenozoic range front deformation that has continued into the Quaternary, and is probably related to a blind thrust fault at depth. The Lawlor Tuff has been found previously to the northwest, in the central Coast Ranges, and to the southeast, in the Kettleman Hills, but this is the first instance of a find on the west flank of the San Joaquin Valley.

9. We have undertaken the study of a suite of tephra collected by Jim Yount and David Harwood from upper Quaternary lake, marsh, and fluvial beds in Mohawk Valley, a faulted half-graben in the northern Sierra Nevada. The suite of ~12 tephra layers range in age from the ~400,000 yr-old Rockland ash bed to the 6850 yr-young Mazama ash bed, and provide age control to this stratigraphic/neotectonic study.

10. We have determined the age of a paleomagnetic event in the Brunhes Normal Chron, and correlated it among five sites, from Pringle Falls, Ore., on the north, to Long Valley Caldera, Calif., on the south, over a distance of ~700 km using the "Orange set" of ash beds.
±17 ka and 187 ±11 ka). This magnetic event thus cannot be the Blake event, as previously proposed, but is more likely the Jamaica or some other event. It correlates well with the marine oxygen-isotope stage 6.

Reports (funded wholly or in part by EQHRP)


Fault Segmentation: San Andreas Fault System
9960-11336, 9960-12336

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Program Element II

Investigations

The objective of the project is to quantify the behavior of the San Andreas fault and major parallel faults in the San Francisco Bay area and in southern California with regard to segmentation, earthquake recurrence intervals, slip rate, and slip per event. These parameters are the primary inputs for long-term probabilistic earthquake forecasting. They were the basic data for the 1988 and 1990 Working Group reports on 30 year earthquake probabilities and are currently being used to revise southern California earthquake probabilities as part of the Southern California Earthquake Center (SCEC) Phase II report. Project work involves paleoseismological studies, primarily trenching, along the Rodgers Creek fault zone in Sonoma County, the Santa Cruz Mountains segment of the San Andreas fault, the Mojave and San Bernadino Mountains segments of the San Andreas fault, and the system of faults associated with the 1992 Landers earthquake.

Results

1. Rodgers Creek fault zone. Work to date has provided estimates of the timing of individual paleoearthquakes and slip rate on this fault. Radiocarbon dates from trenches at the Triangle G Ranch and Beebe Ranch sites indicate that three surface faulting (M7) earthquakes occurred during approximately the past 1000 years. Preliminary constraints on the timing of these events suggest that they occurred at about 1000 AD, between 1200 and 1400 AD, and between 1650 and 1808 AD. The timing of the two most recent events on the Rodgers Creek fault zone appears sufficiently different from the past two events on the Hayward fault, reinforcing the possibility that the 6 km wide step between the two faults may be a persistent segment boundary. The slip rate for the fault is 6.4-10.4 mm/yr for the past 775 years. The investigation indicates that the elapsed time on the Rodgers Creek fault zone is the longest on any major Bay Area fault segment (at least 184 years) and is near, at, or possibly beyond the average repeat time of 230 years.

2. San Andreas fault zone-Santa Cruz Mountains. Analysis has been completed of three trenches excavated across the main trace of the San Andreas fault at Grizzly Flat, 9 km east of the 1989 Loma Prieta epicenter. The trenches exposed evidence of the past two large surface faulting earthquakes. The most recent event displaces all sediments and the ground surface and produced sub-vertical scarplets that are geomorphically fresh. Dendro-corrected radiocarbon dates on detrital charcoal indicate this event occurred after 1800 AD and it is interpreted as faulting from the 1906 earthquake, which is known to have passed through the site. Structural relations and radiocarbon dating suggest that the penultimate
event occurred shortly before 1636-1660 AD. Similar dates for the timing of a pre-1906 earthquake have also been obtained by C. Prentice near Pt. Arena and by T. Hall in Marin County, which suggests a pre-1906 rupture of similar dimensions. If this is the case, the interval between 1906-type earthquakes is about 250 years, a value consistent with calculated repeat times for 1906-type earthquakes but longer than the 125 year average interval used by the 1990 Working Group to estimate probabilities for this part of the fault zone. An important inference is that the Santa Cruz Mountains segment only ruptures during 1906-type earthquakes. Therefore, for long multi-segmented strike-slip faults, there may be master segments that are composed of shorter structural or geometric subsegments. These subsegments may slip only in conjunction with the master segment or, if they slip independently, recurrence may not be periodic.

3. San Andreas fault zone-Wrightwood. Analysis of the timing of the five most recent events at this location on the San Andreas fault, using standard and high-precision radiocarbon dating on peats, was completed and the results were published in Science. Our four year effort resulted in defining events in AD 1857, 1812, 1700, 1610 and 1460. The Wrightwood site contains two more events than Pallett Creek, 25 km to the north, for the same period of time. The 1610 event, and very likely the 1812 event, do not correlate with the event chronology at Pallett Creek and likely involved an independent San Bernadino Mountains segment of the fault. These events decrease estimates of the average recurrence interval on the southern San Andreas fault zone to about 100 years.

4. Landers surface faulting and associated faults.

a) Homestead Valley rupture segment. We are trying to answer questions about "new faulting", characteristic earthquakes, and fault segmentation. Trenching was initiated in January 1993 to develop information on the timing and amount of slip during past earthquakes on the Homestead Valley (central) rupture segment of the 1992 surface faulting. Six trenches have been excavated across the fault in playa and alluvial deposits. They show repeated late Quaternary faulting and we have been able to identify the three most recent large slip paleoearthquakes that occurred prior to 1992. Initial radiocarbon and thermoluminescence dates show that the penultimate event occurred between about 5.7 ka and 8.1 ka and the third event back occurred shortly after 12.5 ka. We have no constraints on the timing of the fourth event. In 1992 right slip at the site was about 3m and vertical displacement ranged from 30 to 40 cm. Although our trenches do not constrain the amount of horizontal displacement from earlier events, initial reconstruction of trench stratigraphy indicates that vertical displacement during the penultimate event was essentially the same as 1992. If vertical to horizontal slip ratios from 1992 reflect repeated behavior, the Homestead Valley fault slipped about 3 m during the penultimate event. The length of the segment (25 km) is short for this amount of offset, which suggests that prior events also involved the rupture of multiple segments.

b) Emerson fault. Two trenches were excavated across the unruptured southeast section of the Emerson fault on the Twenty Nine Palms Marine base to compare the timing of past events with the earthquake chronology being developed by Caltech geologists along the ruptured 1992 segment near Bessemer Mine Road. The trenches exposed only the most recent event, which is expressed as a high angle fault in Holocene deposits with 15 cm of vertical slip and an unknown amount of horizontal. Detrital charcoal indicates that this event occurred after 1.8 ka and is possibly younger than 0.6 ka.

5. Southern California Earthquake Center (SCEC) Phase II Report. D. Schwartz has coordinated a working group of geologists with the goal of developing a consensus on fault slip rates, earthquake recurrence intervals, and maximum magnitudes for the San Andreas fault, San Jacinto fault, Elsinore fault, and other major seismogenic
earthquake sources in southern California. These data will provide major input for the SCEC Phase II report on revised 30 year earthquake probabilities.

**Reports**


INVESTIGATIONS

This project addresses major gaps that currently exist in our understanding of the tectonic setting, seismic source zones, and recurrence intervals of damaging earthquakes in the central U.S., and the integration of surface and subsurface data into seismotectonic models. 1993, the second year of this project, was dedicated to three main activities: 1) paleoearthquake studies in the New Madrid seismic zone; 2) measurement and modeling of active deformation in the central New Madrid seismic zone; and 3) processing and interpretation of shallow seismic reflection data over the Crittenden County fault zone. Each of these is described in more detail in the following section.

RESULTS

Paleoearthquake Studies in the New Madrid Seismic Zone — This part of the project is a collaborative effort with Martitia Tuttle (Lamont-Doherty Earth Observatory) and Yong Li, John Craven, and Michael Ellis (all of the Center for Earthquake Research and Information, Memphis State University). We have found at least 6 sites with evidence demonstrating or strongly suggesting pre-1811 earthquake-induced liquefaction (Tuttle et al., 1993a,b). Sand blows at a minimum of three sites near location A (Figure 1) are between 1,000 and 1,300 years old, based on archeological data. Site 3MS-560, a portion of which is shown in Figure 2, was discovered during a cultural resources (archaeology) assessment of Eaker Air Force Base. Two sand blows are visible, separated by a laterally continuous clay layer. Below the sand units is a silt loam with a
well-developed A-horizon containing artifacts of Late Woodland (B.C. 500 to A.D. 800) and Early Mississippian (A.D. 700 to A.D. 1,000) cultures. A Mississippian cultural layer was also developed above the sand units. Thus, the sands were vented between A.D. 700 and A.D. 1,600. Although the lower vented sand appears more weathered than the upper sand, we have not yet determined if they are significantly separated in age. A nearby site (3MS-525) contains one sand blow that bears the same relationships to the archaeology. A radiocarbon date above the sand blow is 1275±100 years B.P.

At site 3MS-304, located just north of Eaker Air Force Base, a large prehistoric sand blow was exposed in three walls of an exploratory trench. A diagram of the western wall is shown in Figure 3. The sand blow and related dikes cross-cut a very thick, dark brown A horizon which contains occupation layers and Early Mississippian artifacts. The sand blow is crater-shaped and the vent is more than 1 m wide. The vented sand within the crater showed signs of significant soil development. A pit, apparently dug into the sand blow, contained charcoal and early Mississippian artifacts. Based on an archaeological analysis of the assemblage of artifacts, the pit was excavated during the early Mississippian era, sometime between A.D. 700 to 1000. Consistent with the archaeological analysis, radiocarbon dating of charcoal collected from the base of the pit yielded an age of 450 ± 100 years B.P. Two charcoal samples collected from the sandy silt loam higher in the pit yielded modern radiocarbon ages suggesting recent infilling or root growth.

At location B, we have found evidence at two sites indicating two and possibly three pre-1811 liquefaction events, with soil development increasing in progressively older events. Carbon-14 age determinations on wood in an underlying clay deposit show that all events are younger than 5,000 years B.P.

Site WD102-1 (location C) is about 20 km northeast of New Madrid, Missouri. At this site, two sand blows are stacked above a buried A horizon. A 26-cm thick A horizon is developed on the lower sand blow (Figure 4). The lower sand blow and its associated A horizon are crosscut by the feeder dike of the overlying sand blow. A relatively thin (10 cm) A horizon is developed on the upper sand blow. A preliminary date on wood buried by the upper sand blow indicates that this sand deposit probably formed in 1811-1812. This site is within 35 km sites D, E, and F, all of which show evidence for two pre-1811 earthquakes within the past 2,000 years.

Measurement and Modeling of Active Deformation in the Central New Madrid Seismic Zone (in collaboration with Michael Ellis and Robert Smalley, Memphis State University) — Materials and landowners' permissions have been obtained for the installation of 15 anchored GPS monuments in the Lake County uplift area. Ten sites have been constructed. The first GPS measurements were completed in October, but have not yet been analyzed. Development of a 3-dimensional boundary element program has been completed (Gomberg and Ellis, 1993) and copies of the program have been distributed to geophysicists and geologists in the U.S., Germany and Spain for application to a wide range of problems.
Figure 1: New Madrid seismic zone. Diamonds at A, B, C, D, E, and F, paleoseismology sites discussed in text; seismicity from July, 1974, to December 1991, shown in background by cross symbols.
Figure 2: Site 3MS-560, at Eaker Air Force Base, Arkansas (site A in Figure 1). Two sand blows are present, separated by a laterally continuous clay layer. Archeological and carbon-14 data suggest the sands were vented between A.D. 700 and A.D. 1,600. Although the lower vented sand appears more weathered than the upper sand, we have not yet determined if they are significantly separated in age.
Figure 3: West wall of site 3MS-304, just north of Eaker Air Force Base (site A in Figure 1). Archeological and carbon-14 data suggest the sand was vented between A.D. 700 and A.D. 1,600.
Figure 4: Site WD102-1, about 20 km northeast of New Madrid, Missouri (site C in Figure 1). Although the ages of the two sand blows is unknown, the well-developed A horizon on the lower sand suggests it is perhaps a few thousand years older than the upper one. This site is within 35 km sites D, E, and F, all of which show evidence for two pre-1811 earthquakes within the past 2,000 years.
We have used 3D-DEF to explore two fundamental questions about active deformation in the New Madrid seismic zone (Gomberg and Ellis, in press): 1) what is the underlying driving mechanism causing deformation, and 2) how is the deformation accommodated? A variety of reasonable models were used to calculate 3-dimensional surface displacement fields; we model displacements because all other descriptions of the deformation can be derived from them and because they are directly observable, either from geomorphic or geodetic analyses. We find that these fields cannot distinguish between either a far-field simple or a pure shear strain field, or one that involves a deep shear zone coplanar with the upper crustal faults. Thus, neither geomorphic nor geodetic studies are expected to reveal the ultimate driving mechanism behind the present-day deformation. However, predicted surface displacements provide strong constraints on how strain is accommodated in the central step-over (Figure 1). We find that the topographic data favor the existence of two southwest dipping faults, the geometry of which are inferred from micro-earthquake data. The modeling results indicate that, over the long-term, the central shallow dipping cross-fault acts as a reverse fault but that the steeper cross-fault acts as a normal fault. Horizontal displacement fields for models with and without cross-faults differ significantly, suggesting that geodetic surveys should further constrain the existence and geometry of these inferred faults.

Processing and Interpretation of Shallow Seismic Reflection Data over the Crittenden County Fault Zone — In collaboration with Kaye Shedlock (USGS/BELH), Roy Van-Arsdale (University of Arkansas), Lisa Kanter (Memphis State University) and Gene Luzietti (formerly USGS), shallow seismic reflection data (Mini-SOSIE) were collected in 1990 and 1991 along the Bootheel lineament, Crowley's Ridge, the Crittenden County fault zone, as well as several other targets in northeastern Arkansas, southeastern Missouri, and western Tennessee. As part of this project and for his M.S. thesis, David Nicholas has processed and interpreted the 1991 Crittenden County data (Nicholas et al., 1992; Nicholas, 1993). The Crittenden County fault zone, along the southeastern boundary of the Reelfoot rift, is only 40 km west of Memphis, Tennessee. Although nearly aseismic, earlier studies have documented Cenozoic deformation on this structure. Thus, it is significant for regional seismic-hazard analyses. When combined with data previously collected, we now have imaged 30 km of the fault zone with lines spaced approximately every 4 km. The new lines confirm a maximum of 60-70 m of southeast-side-down displacement of Cretaceous through lower Eocene rocks across a monoclinal flexure that contains some minor high-angle reverse faulting. Most of the deformation occurred between deposition of the upper Paleocene-lower Eocene Flour Island Formation and Quaternary/Eocene unconformity. The youngest clear reflector (Quaternary/Eocene unconformity) has only minor relief that we interpret as due to fluvial erosion, but is not imaged well enough to determine if minor Quaternary faulting is present. Throw across the fault zone decreases to near zero directly west of Memphis. The northeastern end of the fault zone is not yet defined.
REPORTS:


Gomberg, J., and Ellis, M., in press, Topography and tectonics of the central New Madrid seismic zone: Results of numerical experiments using a three-dimensional boundary-element program: Journal of Geophysical Research.

Li, Y., and Schweig, E. S., III, 1993, Has the Reelfoot rift zone controlled tectonic activity since the Late Cretaceous? (abstract): EOS, Transactions, American Geophysical Union, v.74, supplement to no. 16, p. 281.


Schweig, E. S., III, and Ellis, M., 1993a, The long-term record of deformation in the New Madrid seismic zone (abstract): EOS, Transactions, American Geophysical Union, v.74, supplement to no. 16, p. 281.


SALTON TROUGH TECTONICS AND QUATERNARY FAULTING

9960-11266

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Program Element II

Investigations

1) Geologic mapping of the southern San Jacinto fault zone in the western Imperial Valley.
2) Post-1987 afterslip on the Superstition Hills fault, the Wienert fault, and the Barth fault.

Results

1) Mapping of Quaternary tectonic features within the San Jacinto fault zone at 1:24,000 scale continued in 1993 in the Kane Spring NW and Shell Reef Quadrangles in the western Imperial Valley. Field work for these quadrangles is near completion. The mapping has revealed the presence of innumerable northwest-trending, steeply inclined faults, each of which right laterally displaces Quaternary strata and fold structures. Although most of these faults have limited horizontal extent and probably small net horizontal component of displacement, the cumulative displacement of the complex assemblage is as yet unknown. Correlation of individual stratal units is difficult owing to the lithologic monotony of the Quaternary sediments in that part of the Imperial Valley. Continuity of individual fault strands that trend parallel to the San Jacinto zone is disrupted by even more abundant northeast-trending left lateral faults, north-south-trending faults with probably dip-slip displacement and at least one major east-west transverse structure.

The recency of surface movement on most of these faults is difficult to assess with geologic and geomorphic evidence. Most faults are exposed in badlands topography where the rate of erosion probably far exceeds the rate of generation of geomorphic expression by surface displacement. However, the high level of seismic activity (at magnitudes mostly less than three in recent decades) suggests that many, if not all, of these faults should be considered as active structures. If and when a major earthquake were to strike in this region, surface faulting would probably be far more complex than the fault pattern that is now revealed by the regional geologic mapping. Such an event would most likely be associated with the conjugate surface faulting of the kind exhibited by the nearby Elmore Ranch and Superstition Hills earthquakes in 1987, but normal faulting on north-south structures would probably be more prominent than that found after the 1987 events.
2) Monitoring of monuments distributed along the length of the Superstition Hills fault has shown general quiescence since the surface movement in June 1992 triggered by the Landers earthquake. The only significant right-lateral surface afterslip (< 0.5 cm) in 1993 took place probably in June or early July along about 3.5 km of the southernmost part of the northern strand. This slip event is unusual compared to others recorded since the fall of 1989 by virtue of its short length; most of the afterslip events over that period had rupture lengths in the range of 10-20 km. Nearly all of the monument stations record slow and probably more-or-less continuous right-lateral drift, ranging between 0 and about 3 cm/yr but mostly less than 5 mm/yr. The absence of a single afterslip event in 1993 that affected most of the 23-km length of the fault probably is a consequence of the 1992 Landers-triggered slip event, which occurred only about 3 weeks after a spontaneously generated surface movement with about the same range of right-lateral slip (0-1.5 cm). A new afterslip event of about the size that ruptures most of the fault length can be expected in 1994.

Coseismic movement associated with the 1987 Superstition Hills earthquake along the southernmost part of the Weinert fault was almost entirely dip-slip in nature, with no obvious right-lateral displacement of cultural features in farmland in the western Imperial Valley. By 1993, a concrete-lined irrigation ditch clearly showed a right-lateral displacement of at least 5 cm. Appearance of a right-lateral component of slip subsequent to a dominant vertical component has been noted previously in the Imperial Valley region only on the Brawley fault (1979) and Imperial fault (late in the 1979 afterslip period). These occurrences suggest that judgment of the tectonic significance of coseismic ruptures should be made with care if the fault orientations are northwestward and a right-lateral slip component appears to be absent.

Reports


A LITHO- AND BIOSTRATIGRAPHIC EVALUATION OF THE COSEISMIC SUBSIDENCE AND INTERSEISMIC STRAIN ACCUMULATION IN THE WASHINGTON AND OREGON PART OF THE CASCADIA SUBDUCTION ZONE.

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INVESTIGATIONS

The two research questions addressed by this project are:

1. Do the alternating peat/mud sequences recorded in the Pacific Northwest reflect earthquake-related events?

2. What is the palaeobotanical evidence for interseismic crustal movements?

We are not concerned directly with attempting to separate eustatic from crustal components, or with generating new relative sea-level curves for the study sites. This project is concerned with testing proposed models of relative sea-level and associated coastal evolution in the PNW (Atwater 1992, Atwater & Yamaguchi 1991). This testing is achieved through the combined use of pollen and diatom analysis in conjunction with a detailed stratigraphic program. Selection of field sites was undertaken in conjunction with USGS scientists (Atwater & Nelson), who were present for part of the field work.

The objectives of this pilot study (May 1993-April 1994) are:

1. To establish the relative importance of local and regional processes reflected in the stratigraphic sequences at Johns River, Grays Harbor.

2. To test the validity of models of interseismic crustal movements through an analysis of the nature of palaeoenvironmental vegetation succession and sedimentation at the site.

3. To specify criteria that can be used to distinguish peat/mud couplets produced by coseismic subsidence.

RESULTS

Site

The site of Johns River comprises a small estuary and intertidal river valley on the south shore of Grays Harbor, north-west Washington. The lower valley contains organic and clastic Holocene deposits which form a record of past environmental changes related to sea level movement. It also contains a suite of contemporary environments which are distributed according to their altitudinal relationship with present sea level. These range from intertidal sand and mudflat through low and high marsh to riverine floodplain and palustrine marshes, fringed by backswamp woodland grading into terrestrial forest. The site provides a range of modern sedimentary environments and ecological communities which can be used as an analogue to interpret the palaeoenvironmental record contained in the valley sediments and reconstruct past sea level history.
Stratigraphy

The lithostratigraphic record at Johns River was subjected to systematic investigation both by the examination of sections exposed in the river bank and by the hand coring of three borehole transects. Each transect extended from the river to the back swamp area which fringes the higher ground at the edge of the river valley, so that the lateral distribution and spatial variation of sediments could be mapped. Because of time considerations, each core was terminated at a maximum of seven metres depth. A total of twenty-one stations were examined and were designated JR93-1 to JR93-21, of which stations 1 and 2 comprised river bank sections extended by coring. Sediments were recorded in the field using the detailed system of notation devised by Troels-Smith (1955) for the characterisation of unconsolidated sediments, which permits objective lithological description. All cores were levelled (accuracy ± 0.01m) to benchmark G 423 1968 at the Johns River bridge to give altitudes relative to NGVD.

The results of the survey can be summarised with reference to transect 1. This includes stations 1, 3, 4, 5 and 6, and contains a stratigraphic succession representative of the whole site. Three fully organic peat layers were recorded in the exposed section of station 1, at c. + 0.75m, -0.15m and -1.10m NGVD respectively, which all comprised a mixture of amorphous organic material and turfa, the decomposed roots and stems of herbaceous plants. These peats had formed in situ, in an environment probably similar to the present day high marsh. The peats were separated by silt and clay with a very low organic component, probably representing intertidal mudflat or subtidal environments. Within the silt-clay lay two thin horizons, termed ‘faint soils’, with a higher organic fraction of around 25% of the total sediment. A further three peat layers were proved in the hand cores 4, 5 and 6, occurring at c. -1.80m, -3.00m and -4.75m NGVD. This lowest peat was recorded in all three cores overlain by a thin sand layer.

In all cases the upper, transgressive, contact of the peat with the silt-clay was very sharp, whereas the lower, regressive, contact was gradual and formed a highly organic transitional layer of several centimetres thickness.

Pollen Analysis

Pollen analysis has been completed on the upper two peat layers, including the highly organic transitional sediments below the peat proper, and the upper faint soil from JR93-1. The results are shown in figures 1 to 3, calculated as percentages of total land pollen. Pollen identification follows Moore et al. (1991).

Both peat layer diagrams (figures 1 and 3) are similar in containing high tree pollen frequencies of about 50% of total pollen, dominated by Picea and Tsuga, with lesser frequencies of Pinus, Alnus and Cupressaceae, the latter probably Thuja rather than Juniperus. The consistent nature of the pollen curves for Picea and Tsuga suggest that these taxa were components of the more regional forest, whereas the fluctuations in the Alnus and Cupressaceae curves, and their lower overall values in figure 3, suggest they were part of the riverine and backswamp woodland and thus affected by environmental changes within the valley wetland caused by water level movements. These changes are expressed most clearly in the herb pollen data. In figure 1 a succession occurs in indicator pollen types as follows: Aster-type and Chenopodiaceae; Cyperaceae; Gramineae; Umbelliferae, Potentilla-type and Menyanthes. It corresponds to the stratigraphic succession from silt-clay through highly organic silt to turfa peat and may be interpreted as showing ecological change from pioneer intertidal mudflat through lower marsh to high marsh plant communities.

The second peat, figure 3, shows a similar direction of ecological change, passing from Chenopodiaceae and Triphlochin in the lower succession to Potentilla-type near the top of the peat. This diagram is heavily dominated by Gramineae pollen, however, which may reflect water level and quality which differ from that of figure 1, or simply local variability through time in the marsh community.

The pollen record from the faint soil, compared with the other two diagrams, suggests a relative fall in water level and the establishment of a pioneer upper intertidal mudflat community with lower marsh environments nearby, followed by a sudden revertance to lower intertidal conditions.
Chenopodiaceae dominates within the faint soil and Aster-type, Artemisia and Triglochin are all present. The sharp fall in Chenopodiaceae and Aster-type and the rise in Alnus above the faint soil layer suggest an increase in water depth and the replacement of pollen from local vegetation by extra-local waterborne pollen.

Diatom Analyses

Diatom analyses have been completed through both the organic and clastic deposits in the same sequence. Over 200 valves were counted from each level, identification following van de Werff & Huls (1958-1974), and the frequencies of each species are expressed as percentages of total diatom valves in Figures 4 and 5. Based on the present knowledge of the contemporary diatom flora of estuarine or saltmarsh environments in Oregon (Nelson & Kashima 1993), diatom assemblages from the sections examined are interpreted and categorised provisionally into zones in relation to depositional environments, i.e. subtidal flat, lower intertidal mudflat, pioneer saltmarsh, low marsh and high marsh.

Diatom assemblages of subtidal flat (zones Sb and Sc) are characterised by Thalassiosira eccentrica, Thalassionema nitzschioides, Navicula crucifera, Mastogloia pumila and Cymatosira belgica, along with Achnanthes delicatula, Amphora coffeiformis, Amphora salina and Navicula cari var. cincta. Total percentages of polyhalobian and mesohalobian taxa are high and up to 40-60% and 30-40% respectively, probably representing a subtidal environment. Lower intertidal mudflat is suggested by zones la, lb and lc. Important diatom species in these zones include Cymatosira belgica, Caloneis westii, Nitzschia sigma, Navicula cari var. cincta and Navicula trivialis. Percentages of mesohalobian taxa (30-40 %) are higher than those of polyhalobian taxa (20-30 %), with occurrence of oligohalobian-halophile and oligohalobian-indifferent taxa. In the pioneer saltmarsh (zones Pa, Pb and Pc), the diatom assemblages are quite similar to those in the lower intertidal mudflat, except for the high frequencies of Navicula pusilla and the occurrence of Pinnularia borealis, resulting in a higher percentage of total oligohalobian taxa. Macrofossil saltmarsh rootlets are found in the sediments associated with this diatom group. In low marsh sediments (zones La, Lb and Lc), oligohalobian-indifferent taxa are normally dominant in the diatom assemblages. Characteristic taxa include Navicula pusilla, Pinnularia borealis, Nitzschia fruticosa, with Navicula trivialis and Navicula cari var. cincta in some cases. The organic silty clay associated with these zones is also a feature of the low marsh sediment. Finally, diatoms of oligohalobian-indifferent taxa are almost completely dominant in the high marsh samples (zones Ha and Hc). Numerous taxa in these zones are the same as those in low marsh, but characteristically there are higher frequencies of Achnanthes lanceolata and oligohalobian halophobes such as Navicula contenta and Eunotia arcus.

Vertical alternation of these zones reveals the significance of environmental changes. Zones la to Ha illustrate a process of gradual sediment accretion leading towards a high marsh environment. The diatom assemblage of zone Sb is markedly different to that of zone Ha, with a great amount of broken valves in the lowest two levels, suggesting a sudden change from high marsh to subtidal environment, in other words, an instantaneous marine inundation. Zones Sb to Lb represent another period of processes of gradual sediment accretion but never reach the high marsh stage. Also importantly, the change from zone Lb to lc (at the top of the faint soil) seems to be quite rapid. Further upwards, a process of gradual sediment accretion leading towards high marsh is indicated by zones lc to Hc. This is followed by another sudden change from high marsh to subtidal environment and an instantaneous marine inundation, at the base of zone Sc.

Laboratory programme for the rest of the Project (November 1993-April 1994)

The pollen and diatom analyses have been proven, in conjunction, to be sensitive indicators of palaeoecological conditions. The pollen flora allows the reconstruction of plant communities which may then be related to a position on the ecological gradient across the tidal marsh based on elevation relative to sea level. The diatom flora is closely diagnostic of palaeosalinity and can accurately reveal the environment of deposition of the various Johns River sediments, again relative to sea level, from subtidal to high marsh. Analyses of the two peat layers presented here suggest that the establishment of high marsh conditions occurred gradually, whereas the transition from high marsh to tidal or subtidal mudflat was swift. The faint soil evidence is of lesser magnitude, but
seems to follow the same trend.

Future work includes the application of the same analysis techniques to the four deeper peat layers to see whether any variation in this pattern occurs, in particular whether any signal of background sea level fluctuation may be discerned in the earlier examples, which appears to be missing in the two upper peats. One of the peat formation episodes will be examined in more than one core, so that any spatial differences in the effects of rapid or gradual sea level change within the Johns River valley may become apparent. Quantitative analyses of the pollen and diatom data using multivariate techniques will be undertaken once the data collection is complete.

References


van de Werff A. & Huls H. (1958-74) *Diatomeenflora van Nederland* 8 parts. Published privately by van de Werff A., Westzijde, 13a, De Hoefz(?)
Figure 1. Pollen diagram from peat 1. Key to stratigraphic symbols: black = peat, stippled = highly organic silty clay, blank = silt-clay
Johns River 93–1
upper faint soil

Figure 2. Pollen diagram from upper faint soil. Stratigraphic symbols as in Figure 1.
Figure 3. Pollen diagram from peat 2. Stratigraphic symbols as in Figure 1.
Figure 4. Diatom diagram from peat 1 and upper faint soil. Stratigraphic symbols as in Figure 1. Diatoms below 5% grouped as 'Others'. 
Figure 5. Diatom diagram from peat 2. Stratigraphic symbols as in Figure 1. Diatoms below 5% grouped as 'Others'.

Johns River 93-1

peat 2
Investigations

[1] Real-time monitoring, analysis, and interpretation of strain, creep, magnetic, tilt and other low frequency data within the San Andreas fault system and other areas for the purpose of understanding and anticipating crustal deformation and failure.

[2] Enhancements to satellite-based telemetry system for reliable real-time reporting and archiving of crustal deformation data.

[3] Specialized monitoring, including automated alerts, and display of data relevant to the earthquake program and specific to regions such as Parkfield, Mammoth Lakes, and the San Francisco Bay area.

Results

[1] Data from low frequency instruments in Southern and Central California have been collected and archived using the Low Frequency Data System. During the year measurements from over 100 satellite platforms (most reporting at ten minute intervals) have been received via satellite telemetry and subsequently archived by Low Frequency Network computers for analysis.

[2] The project has operated a configuration of two Sun workstations for use as data archiving, monitoring, and analysis systems. Both workstations receive satellite telemetry in near real-time from a PC-based system which acts as a satellite downlink. Data from the Network are available to investigators in near real-time and software for data display and analysis is available. Tectonic events, such as creep along the fault, can be monitored while still in progress.

[3] The project uses a 1.8 meter satellite receiver dish installed in Menlo Park for retrieval of near real-time surface deformation data from California and South Pacific islands. The GOES geostationary satellite in conjunction with a domestic communications satellite provide the telemetry which makes possible a reliable real-time data collection system. Further expansion of the number of platforms monitored, particularly in the San Francisco Bay area is ongoing. Instrumentation added to the telemetry system in the Bay area during the year includes strainmeters and GEOS recorders. The GEOS recorders transmit summarized seismic event data, as well as instrument status reports.

[4] The project continues to take an active part in the earthquake prediction activities. Automated alerts for signals which may indicate anomalous tectonic activity notify personnel in near real-time. Data collection and computer operations are automatically monitored for abnormal activity and project members are paged for in the event of problems with either.
As part of the Bay Area region study, display facilities have been enhanced to provide improved monitoring and other graphic displays for scientists, the media, and the public. During the year a new computer display was added to the facility located in the Menlo Park Building 7 lobby. The area has been used extensively by the media, especially during periods such as public earthquake prediction alerts.
PALEOSEISMIC INVESTIGATION OF THE NORTHERN CALAVERAS FAULT

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TECHNICAL ABSTRACT

Investigations
The purpose of this study is to assess the location, history and seismic potential of the northern Calaveras fault through paleoseismic trenching investigations. Our previous research resulted in the definition of four distinct physical fault segments of the Calaveras fault north of Calaveras Reservoir (Simpson and others, 1992) and an underlying motive of this phase of our research is to test this segmentation model. In previous phases of our study, we identified five paleoseismic study sites that we believe represent the last undisturbed sites along the northern Calaveras fault, much of which passes through the rapidly developing communities of Pleasanton, San Ramon, and Danville. For this study, we plan to excavate paleoseismic trenches at two of these sites. Prioritization of the five sites is based on our desire to test the segmentation model, particularly as it relates to the Alamo segment, which is related to the poorly understood transfer of slip from the Calaveras fault to the Concord fault to the northeast. For this reason, we are studying the Calaveras fault at Camille Lane in Alamo to assess fault activity at the northernmost end of apparent geomorphic expression. In addition, we are studying the fault at the north end of Sunol Valley. This site is a high priority at this time because we are currently permitted by the San Francisco Water Department to conduct our investigation; future access may be difficult to obtain.

Results
The four fault segments defined in the initial phase of this study are, from south to north: the Calaveras Reservoir, Sunol Valley, San Ramon, and Alamo segments. These segments range in length from 7 to 23 kilometers and are defined primarily by geomorphic expression, fault geometry, seismicity, intersecting structures, and range-front orientation. If the identified segments represent independent fault rupture segments, the northern Calaveras fault probably ruptures in moderate magnitude (M 6½) earthquakes. If two or more segments rupture during a single event, empirical regressions suggest maximum magnitudes ranging from M 6½ to 7½.

To date, we have nearly completed our investigations at one of the two sites we hope to study this year. The first part of our investigation was conducted in an orchard adjacent to Camille Lane in Alamo, CA. The Camille Lane site is located across the northernmost geomorphic features which have, in the past, been interpreted to be associated with the Calaveras fault. A large prominent scarp, 4- to 6-m high, is present to the north and south of the site. This scarp, together with subtle tonal lineaments crossing an alluvial fan at the site were cited by Herd (1981) as evidence of Holocene activity along this part of the Calaveras fault. Later, Hart (1981) concluded that compelling evidence of Holocene activity is not present and decided not to include this part of the fault within the State's Alquist-Priolo Special Studies Zone. The uncertainty about the presence or absence of
recent movement along the northern Calaveras fault within the Alamo segment is the primary motivating factor for study at this site.

We excavated a 43-m-long, 5-6 m deep trench at the Camille Lane site along the axis of an alluvial fan, across the projection of the bedrock scarp. The trench exposed a thick sequence of fine-grained alluvial deposits. These deposits consist of clayey and sandy silts with local pebble lenses. There was no evidence of faulting or fault-related deformation within our trench. Although the stratigraphy exposed in our trench was subtle, and the fine-grained nature of the materials has resulted in strong prismatic soil structure, we are confident that we would be able to detect significant fault-related deformation. The excavation was logged in detail at a scale of 1" = 1m. Significant amounts of charcoal were collected in the trench (37 samples), and selected samples are currently being prepared for radiometric dating. We hope that these samples will aid us in dating the alluvial materials at the site, and they may provide a minimum age for the most recent faulting along this segment of the fault.

Remaining Tasks
We are currently attempting to gain access to private property immediately south of the Camille Lane trench site that lies astride the bedrock escarpment. We hope to excavate a small trench across the scarp to verify that this linear feature is a tectonic scarp. Confirmation of the tectonic nature of this feature will allow us to constrain the location and timing of late Quaternary movement along the Alamo segment of the northern Calaveras fault.

The second site we plan to investigate this year is within a ridge-top graben along the Calaveras fault at the northern end of the Sunol segment (northern end of Sunol Valley). The graben is about 10 to 15 meters wide and a thick sequence of colluvial/fluvial deposits has accumulated via sheet wash from the surrounding hillslopes. This colluvial/fluvial stratigraphy should provide an excellent record of displacement and colluvial wedge formation at the site. This trench should allow interpretation of the number and timing of previous earthquakes and should help clarify the nature of the segment boundary between the Sunol and San Ramon segments of the fault.

Publications


Digital Data Analysis

9920–10112

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Investigations

1. **Moment Tensor Inversion.** Apply methods for inverting body phase waveforms for the best point-source description to research problems.

2. **Other Source Parameter Studies.** Apply methods for inverting body phase waveforms for distributed kinematic and dynamic source properties.

3. **Aftershock Source Properties.** Examine mainshock and aftershock source properties to study the mechanics of aftershock occurrence.

4. **Earth Structure.** Use long-period and broadband body phases to study lateral heterogeneity, attenuation, and scattering in the crust and mantle.

5. **Network Activity.** Participate in international endeavors aimed at increasing the installation, deployment, and operation of modern worldwide digital seismic networks, especially within areas where seismic-station coverage is poor, for the routine reporting of earthquake arrival-time information.

6. **Data Services.** Provide seismological data and information services to the public and to the seismological research community, particularly data from the Global Digital Seismograph Network (GDSN) on SEED tapes, Network-Day tapes, Network-Event tapes, and Network-Event CD-ROMs.

7. **NEIC Monthly Listing.** Contribute both fault-plane solutions (using first-motion polarity) and moment tensors (using long-period body-phase waveforms) for all events of magnitude 5.8 or greater when sufficient data exists. Contribute waveform/focal-sphere figures of selected events.

Results

1. **Moment Tensor Inversion.** A paper listing the moment-tensor solutions for 108 moderate-to-large size earthquakes occurring in 1991 has been published and a paper listing the moment-tensor solutions for 133 moderate-to-large size earth-
II

quakes occurring in 1992 is in press. We have implemented a procedure, now in routine use, for the rapid estimation of moment-tensor solutions using near-real-time USNSN, GTSN, and IRIS/GSN data. On the order of 12 earthquakes per month are being analyzed using this new system. These solutions are sent by e-mail to over 150 investigators worldwide. A paper analyzing an anomalous tsunamigenic seismic event near Tori Shima, Japan, in which we hypothesize that the causative process was magma injection, has been published. This paper represents the first widely accepted demonstration of magma injection inducing teleseismically observed, long-period seismic radiation. A paper describing a new method for displaying and comparing earthquake mechanisms and assessing and quantifying their similarities and differences is in press.

2. **Other Source Parameter Studies.** Linear and nonlinear methods of waveform inversion are being implemented to derive the distributions of fault slip and rupture time as a function of position on the earthquake fault. These methods have been applied mostly to teleseismic and strong-motion body-wave data although other seismic-wave types can be easily incorporated into the inversion scheme. An application of this technique to two large Mexican subduction-zone earthquakes has been published. A recent innovation of the method involves the recovery of the slip duration on the fault in addition to the fault-slip pattern. This variable rise-time capability allows a complete derivation of the temporal evolution of the coseismic rupture. This approach has been used to study the 1979 Petatlan, Mexico, earthquake, the 1985 Chile earthquake, and the 1989 Ungava, Canada, earthquake. Results for the Chile earthquake have been presented at the Second International Symposium on Andean Geodynamics held in Oxford, England, and have also been submitted for publication. This study involved the inversion of local strong ground motions, teleseismic body waves, and long-period Rayleigh waves. The Petatlan study, which revealed a single circular asperity source for the earthquake, is being submitted for publication. The Ungava results are being incorporated into a broader study of intraplate North American earthquakes. In addition, a summary of the method and its application is being prepared in the Spanish language for publication in a special issue of Fisica de la Tierra.

3. **Aftershock Source Properties.** A study comparing the locations of aftershocks following the 1979 Petatlan, Mexico, earthquake with the pattern of mainshock slip derived from a finite-fault inversion is in progress. Preliminary results suggest that the two clusters of intense aftershock activity observed in the source region occur at the edges of a single circular source zone.

4. **Earth Structure.** Data sets of long-period and broadband shear-wave data have been assembled for the purpose of studying lateral heterogeneity, attenuation, and deep discontinuities in the earth. A paper describing regional variation of attenuation and shear velocity beneath China is in press. In this paper, we show that the crust and upper mantle beneath China are not in thermal equilibrium and hypothesize that this is due to strain heating resulting from the collision of
the Indian sub-continent with Eurasia. A companion paper detailing mantle discontinuity structure beneath China is in preparation.

5. **Network Activity.** Participation in the Middle America Seismograph (MIDAS) program continues, including attendance to the second meeting of the MIDAS consortium held in conjunction with the SSA annual meeting. Also, an overview of the current status of the MIDAS program was presented at the SSA meeting. Collaboration with the Universidad Nacional Autonoma de Mexico is also continuing in the installation of the Mexican national network of digital seismograph stations.

6. **Data Services.** FORTRAN software to read and extract digital data from station tapes (1976-1979) and network day tapes (1980-1987) has been developed and distributed to the research community worldwide. Users are supported on a variety of computers. A new Standard for the Exchange of Earthquake Data (SEED) has been created and tapes are now being produced (1988 to present) and distributed by the Albuquerque Seismic Laboratory. FORTRAN software has been developed to read and extract the digital data from the SEED tapes and this software is being made available to the research community. Event tapes have been produced from net-work day tapes for data from 1980 through 1987 for all events with magnitude 5.5 or greater. Data from the event tapes are reformatted and sent to a CD-ROM mastering facility for replication. Nine volumes have been produced, covering 1980 through March 1987. The CD-ROMs are being distributed to over 220 universities across the United States and geophysical research institutions worldwide. Negotiations have been completed concerning the production of the first Federation of Broadband Digital Seismograph Network (FDSN) CD-ROM. Retrieval software, SONIC (C) and CDRETRV (FORTRAN), has been developed for the IBM/PC/AT/386 compatibles and distributed, allowing easy access to the digital data. There were special requests for waveform data from 59 earthquakes in 1993. The digital data from these events were either mailed on floppy diskette or transferred via e-mail. Fault motion color plots are produced for all large or otherwise significant earthquakes.

7. **NEIC Monthly Listing.** Since January 1981, first-motion fault-plane solutions for all events of magnitude 5.8 or greater have been contributed to the Monthly Listings. Since July 1982, moment-tensor solutions and waveform/focal-sphere plots have also been contributed. In the last year, solutions for 144 events have been published. A series of maps depicting seismicity of the eastern Mediterranean area were prepared for the Office of Earthquakes, Volcanoes, and Engineering. Seismicity maps in the “Earthquake Histories of the Conterminous United States” were updated with data from 1800 through 1993.
Reports


Revenaugh, J., and Sipkin, S.A., 1992, Mantle discontinuity structure beneath China based on multiple-ScS reverberation mapping [abs.]: EOS (American Geophysical Union, Transactions), v. 73, p. 408.


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Seismicity, Ground Motion, and Crustal Deformation
Wasatch Front, Utah, and Adjacent Intermountain Seismic Belt

1434-93-G-2448

Element II. Evaluating Earthquake Potential

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Investigations: October 1, 1992 - September 30, 1993

1. GPS measurements of crustal deformation along the Wasatch fault.
2. Aftershock rate decay and earthquake clustering in the Utah region.
3. 2-D and 3-D modeling of site amplification in the Salt Lake Valley.

Results

1. We have completed the second year of a three-year project (1992-94) to measure deformation rates along the Wasatch fault using Global Positioning System (GPS) technology. Key objectives include (a) a comparison of contemporary deformation with historical seismicity and paleoseismicity and (b) an improved understanding of strain accumulation on normal faults.

Determination of 1938-1992 strain rates along the central Wasatch fault. We worked with Richard Snay of the NGS to determine strain rates along the central Wasatch fault by comparing benchmark locations determined by our 1992 GPS survey (see last annual report) to those determined by geodetic surveys done in 1938, 1962, and 1974. The standard errors for the 1992 GPS measurements are typical for high precision GPS surveys: 3 to 5 mm in latitude, 2 to 5 mm in longitude, and 8 to 12 mm in altitude. The total network solution for the time period 1938 to 1992 (Figure 1) yields a strain rate tensor with principal axes of $83 \pm 13$ nanostrain/yr extension oriented N48°E and $22 \pm 13$ nanostrain/yr oriented N42°W. The largest principal strain rate is nearly twice that determined by Savage et al. (1992, *JGR* 97, 2071-2083) for 1972-1990 from trilateration measurements across the Wasatch fault in the northern part of our 1992 survey area. Over the 70-km width of the network, this principal strain rate translates to a NE extension rate of nearly 6 mm/yr. This extension rate is much higher than would be expected from the Wasatch fault’s long-term slip rate of 1 to 2 mm/yr determined from paleoseismic studies, and is approximately half of the contemporary extension rate across the entire Great Basin.

*S. Hill, K.B. Olsen, G.T. Schuster, and R.A. Snay also contributed significantly to the work reported here.
Figure 1. Map Of Wasatch Front Seismicity and GPS Stations. A) Map of GPS sites: solid diamonds = 1992 GPS Survey, open diamonds = 1993 GPS Survey, triangles = planned 1994 GPS Survey, and solid circles = USGS Trans Basin-Range 1992 GPS Survey. The large arrow indicates the direction of the 6 mm/yr maximum horizontal extension derived by comparing the 1992 GPS survey with a 1938 survey. B) Seismicity, 1900 to March 1990, Quaternary faults, and previous estimates of extension rates in the Wasatch Front region. The extension rates (in mm/yr) have been determined in the outlined regions by summing moment tensors of historical earthquakes (top value) and from geological data (lower value); arrows indicate the directions of the maximum horizontal extension determined from the moment tensor analysis (from Eddington et al., 1987, in *Continental Extensional Tectonics*, 371-392). The EDM-determined rate in the Ogden-Salt Lake City area is from Savage et al. (1992, *JGR* 97, 2071-2083). The labels in A identify the areas of approximately homogenous deformation for which extension rates and directions were estimated: HV = Hansel Valley, CV = Cache Valley, NWF = northern Wasatch fault, SWF = southern Wasatch fault, and SSL = south Salt Lake.
If the strain rates that we measured represent strain accumulation on the Wasatch fault, then the loading rate would be much higher than previously suspected—a finding that would have important implications for earthquake hazard evaluations in the Wasatch Front region. However, our results are still preliminary, and our strain rate estimates may be too high. Ongoing work will test the assumptions of spatial and temporal strain homogeneity by computing strain rates for subsets of the network and the historical geodetic data.

1993 Northern Wasatch Front GPS Survey. The 1993 GPS field campaign focused on reoccupation of existing triangulation and trilateration sites in a 120-km-wide area encompassing the northern Wasatch fault zone (Figure 1). Activities included (1) extensive field reconnaissance, (2) training of personnel, (3) 10 days of field measurements in August 1993, much of it in very rugged terrain, and (3) subsequent data processing using the University NAVSTAR Consortium (UNAVCO) version of the Bernese 3.4 GPS processing software. The 1993 field work was a collaborative effort involving 30 observers from 9 government agencies and Universities: the University of Utah, Utah Geological Survey, UNAVCO, Salt Lake, Weber, Davis, Box Elder, and Cache County Surveyors, and the Bureau of Land Management.

Twelve Trimble 4000 SSE dual frequency p-code receivers and two Trimble 4000 Geodesist-P receivers were operated at 50 sites during the campaign. Thanks to the excellent participation from local agencies, nearly twice as many sites were observed as originally proposed. The majority of the results demonstrate very high precision, comparable to those obtained in 1992. The 1992 base station on the University of Utah campus, however, could not be reoccupied because of microwave interference from a new state communications link. Consequently, we established a new base station which will be carefully located to provide a consistent reference system. The 1993 GPS results will be compared with the 1992 GPS results and historical triangulation and trilateration surveys to obtain estimates of crustal deformation.

2. The goal of this multiyear task is to investigate space-time variations in (a) aftershock behavior (rate decay and duration) and (b) earthquake clustering in the Utah region and their relation to regional tectonic processes and earthquake potential. For modeling aftershock rate decay, we have so far used the well-known modified Omori relation, \( N(t) = \frac{K}{(t + c)^p} \), where \( N(t) \) is the number of events per unit time at time \( t \) after the main shock, and \( K, c, \) and \( p \) are constants. These constants are determined, together with their standard errors, by a maximum-likelihood procedure. For composite clusters (artificial combinations of neighboring microclusters time-shifted to a common main-shock time), we designate the Omori decay exponent as \( p^* \).

The Utah earthquake catalog since 1974 contains more than 13,000 events, including 6,409 events of \( M \geq 1.5 \), and 11 independent main shocks of \( 4.5 \geq M \geq 6.0 \). Aftershock sequences for the latter have \( p \) values ranging from 0.6 to 1.0. Applying the clustering algorithm of Reasenberg (1985, *JGR 90*, 5479-5495) to the 1974-1992 catalog (\( M \geq 1.5 \)) yields 3,812 events belonging to 473 microclusters of two or more events. A remarkable result is unusually weak earthquake clustering in the general vicinity of the Wasatch fault, confirming a similar result obtained by Shimizu (1987, *M.S. thesis, M.I.T.*, 149 pp), who applied the cluster-analysis algorithm of Veneziano and Van Dyck to the Utah catalog (\( M \geq 2.0 \)) for 1962-1985. Our results show unusually weak clustering, even at the microcluster level, within
a linear N-S belt of intense background seismicity about 15 to 40 km east of the westward-dipping Wasatch fault. Another striking example of anomalous earthquake clustering in Utah was the occurrence of only two aftershocks of $M_C \geq 2.0$ following the September 1992 $M_L 5.8$ St. George earthquake in SW Utah.

We have compared spatial variations in $p^*$ with deformation rates determined from historical seismicity, but found no significant correlation. However, comparing spatial variations in $p^*$ and $p$ with surface heat flow in the Utah region shows a tendency for positive regional correlation, as found by others in southern California. An increase in aftershock rate decay (higher $p$ values suggesting shorter stress relaxation time) with heat flow is shown both by the average decay rates for the composite clusters and by the majority of the $p$ values for individual earthquake sequences. We calculated an average $p^*$ value of $0.77 \pm 0.03$ for the entire Utah region by compositing all clustered earthquakes $\geq M2.0$. This compares to an arithmetic mean of $0.82 \pm 0.30$ for individual $p^*$ values from twelve $1^\circ \times 1^\circ$ geographic cells encompassing most of the seismically active parts of Utah.

3. To gain a better understanding of the factors responsible for site amplification in the Salt Lake Basin, we have compared seismograms of steeply-incident (12° from vertical) teleseismic P waves to results from 2-D and 3-D numerical simulations of vertically-incident plane P waves striking the basin. The data were recorded at two temporary 3-component stations of the Utah seismic network. One station was located on thick Quaternary alluvium in the Salt Lake Valley; the other, 8 km away on a Cambrian quartzite outcrop at the eastern edge of the valley. We computed the numerical simulations with a 4th-order staggered-grid finite-difference technique. For the 3-D simulations, we used a two-layer basin model representing semi-consolidated sediments surrounded by bedrock. The models used for the 2-D simulations were based on a vertical cross section of the 3-D model near the two recording stations. Some of the 2-D models incorporated features which could not be included in the 3-D model due to computer limitations, namely topography, a near-surface velocity gradient in the bedrock, and a near-surface layer of low-velocity unconsolidated sediments in the basin. Each set of synthetic seismograms was convolved with a least-squares filter designed to match the synthetic vertical-component record at the rock site to the observed vertical-component record in both waveform shape and amplitude.

The data for the teleseism show only about a 10% amplification of the initial P wave at the alluvium site compared to the rock site, but considerable amplification of the P-wave coda, especially on the horizontal components (compare traces labeled ROCK(O) and SOIL(O) on Figure 2). The 3-D synthetics (S1, Figure 2) overestimate the amplification of the initial P wave and underestimate the amplification of the coda at the alluvium site, as can be seen in Figure 2 by comparing the observed (O) and synthetic (S1) seismograms and plots of cumulative kinetic energy versus time for the data (circles) and the synthetics (asterisks). The large amplitude of the initial P wave in the synthetics is due in part to constructive interference between the direct wave and the reflection from the bottom of the sediments. The amplitude of the initial P wave is significantly smaller in the synthetics for a site 2.7 km NNW of the recording site (S2, Figure 2), where thinner sediments (300 m versus 500 m) produce a weaker interference pattern. This observation, together with the results of some 1-D simulations, shows that the amplitude of the initial P wave in the synthetics is sensitive to variations in
Figure 2. Comparison of observed (O) teleseismic P waves (incidence angle 12°) with 3-D synthetic seismograms (S) for vertically-incident plane P waves recorded at an alluvium site in the Salt Lake Valley (SOIL) and a nearby rock site (ROCK). The data are from an $m_b$ 5.9 earthquake which occurred near the Fiji Islands on Oct. 10, 1990. The synthetics labeled S1 are for the alluvium site where the data were recorded, and those labeled S2 are for another site 2.7 km to the NNW. The graph in the lower right panel shows plots of cumulative kinetic energy per unit volume (one half density times the integral of the vector velocity squared) versus time for the data (circles), the 3-D synthetics (asterisks for S1, X's for S2), and various 2-D synthetics, all normalized to the maximum value for the data. The 2-D synthetics were computed using a vertical cross section of the two-layer 3-D model (pluses), and some modified versions of this model which included some or all of the following features as indicated in the key: a near-surface velocity gradient in the bedrock (ROCK GRAD), topography (TOPO), a near-surface layer of low-velocity unconsolidated sediments in the basin (BASIN LVL), and attenuation ($Q = 250$).
sediment thickness which are below the estimated accuracy of our 3-D model (S.D. ~ 250 m).

Plots of cumulative kinetic energy versus time for 2-D synthetics computed with models incorporating the refinements mentioned above show that the amplitude of the coda is greatly enhanced by the presence of a near-surface layer of low-velocity unconsolidated sediments (Figure 2). 2-D synthetics for a model which has this feature, a basin Q of 250, and a total sediment depth of 360 m at the recording site provide a good match to the observed cumulative kinetic energy curve (compare solid curve with circles, Figure 2). Our results suggest that the large-amplitude coda observed at the alluvium site is primarily due to reverberations in near-surface unconsolidated sediments, whereas the amplification of the initial P-wave arrival is mostly due to the impedance decrease and resonance effects associated with the deeper basin structure.

Reports and Publications


INVESTIGATIONS

1. We studied how static stress changes accompanying earthquakes may trigger other events, focusing on the Landers, California, earthquake sequence.

2. We are analyzing the coseismic deformation and stress changes associated with the following large earthquakes: 1952 M=7.3 Kern County (California), 1954 M=6.9 Dixie Valley and M=7.1 Fairview Peak (Nevada), 1989 M=7 Loma Prieta (California), 1992 M=7 Cape Mendocino (California).

3. We have investigated the creation of sea-floor topography at slowly-spreading mid-ocean ridges that is caused by magmatic accretion and surface faulting.

RESULTS

Static Stress Changes and the Triggering of Earthquakes: Landers Sequence. To understand whether the 1992 M=7.4 Landers earthquake changed the proximity to failure on the San Andreas fault system, we examine the general problem of how one earthquake might trigger another. We use the Coulomb criterion, in which changes in both the shear and normal stress influence a fault's tendency to failure. As a result of an earthquake, the Coulomb stress change on a particular fault depends on its geometry, sense of slip, and the coefficient of friction. We consider a Coulomb criterion appropriate for the production of aftershocks, where faults most likely to slip are those optimally orientated for failure as a result of the regional stress and the stress change caused by the main shock. We use a 50-patch variable-slip model of the Landers earthquake. We find that the distribution of aftershocks for the Landers earthquake, as well as several other moderate events in its vicinity, can be explained by the Coulomb criterion: aftershocks are abundant where the Coulomb stress on optimally orientated faults rose by more than one-half bar, and aftershocks are sparse where the Coulomb stress dropped by a similar amount. We also find that the near-fault rotation of stress axes are consistent with the stress rotations predicted from the Coulomb calculations. We find that several moderate shocks raised the stress at the future Landers epicenter and along much of the Landers rupture zone by about a bar, advancing the Landers
shock by perhaps a century. The Landers rupture, in turn, raised the stress at site of the future
M=6.5 Big Bear aftershock site by 3 bars, and together the Landers and Big Bear earthquakes
raised the stress along the San Bernardino segment of the southern San Andreas fault by 5
bars, hastening the next great earthquake there by about a decade (Stein, King, and Lin).

1989 Loma Prieta Earthquake Deformation: Thrust and Strike-slip Motion.
Leveling surveys conducted before and after the Loma Prieta earthquake provide observations
of the coseismic elevation changes. These data are used to define the spatial pattern of
elevation change, and to deduce the faulting geometry and distribution of slip. Both planar
and curved (listric and negatively listric) faults produce elevation changes consistent with the
observations. Using an elastic halfspace, we treat the data as correlated observations and find
that 60% of the observed signal can be modeled with a planar rupture surface that extends
from 6- to 12-km depth, is 32 km in length, 7 km wide and dips 64°s southwest. With a slip
magnitude of 3.6 m, this model fault produces a geodetic moment of \(2.6 \times 10^{19}\) N·m. A
larger thrust component is found northwest of the epicenter (rake=144°) and a larger strike-
slip component is found southeast of the epicenter (rake=157°). Models with larger rake
variations (>40°) reduce marginally the fit to the data, but require a moment of only \(1.8 \times 10^{19}\)
N·m. The rupture plane lies 2 km southwest of the aftershock zone. When a low-modulus
layer or wedge model is added for consistency with the seismic P-wave velocity structure, the
fault deepens and locates adjacent to the aftershock zone, coming within 1.5 km of the
hypocenter (Marshall and Stein).

A critical element of the Humboldt County infrastructure is its vertical control network. The
positions of bench marks (BMs) in the network are used for cadastral, roadways,
engineering, and flood plain surveys. At the request of the Department of Public Works of
Humboldt County, 333 km of the network nearest the 1992 Cape Mendocino earthquake was
resurveyed by the National Geodetic Survey in late 1992, with 100 new BMs emplaced.
Comparing the new heights with those measured before 1992 gives the vertical deformation
associated with the earthquake, which includes motion caused by slip on the earthquake fault,
earthquake-triggered surficial disturbances such as landslides and liquefaction, and settling of
engineered structures due to earthquake shaking. We find that 37 BMs in Humboldt County
display height changes that can not be accounted for by the earthquake fault slip, and thus
indicate monument, soil or structural instability: 18 BMs show subsidence caused by
groundwater withdrawal in the Eel River basin; 16 BMs show residual movement of less than
a few centimeters, and 4 BMs show major disturbance of up to 4 m. One of the disturbed
BMs lies near an earthquake-induced tension crack, and another is near the site of liquefaction
in the Salt river bed. Nine of the disturbed BMs are set in bridge abutments or highway
overpasses, and 6 are set in retaining walls, and thus might be indicators of structural
weakness or incipient failure. In addition, the distribution of landslides, liquefaction, and road
cracking reveals other sites of potential ground failure along highways, seawalls, and
foundations. Some 1992 BMs could be resurveyed to monitor subsequent movement. Using
a model for the earthquake fault slip that best fits the geodetic and seismic observations of the
earthquake, we infer the uplift of shoals and rocks offshore Humboldt County. We estimate
that 13 shoals lying in less than 3 fathoms (5.5 m) of water were uplifted by more than 0.45
fathoms (0.83 m), presenting increased hazards to coastal navigation. In addition, a 4 x 8
nautical-mile wide (7 x 14 km) zone is identified as the site of potential seafloor faulting with
displacement of up to 3 m, and the head of Mattole Canyon is suggested as the site of possible
seafloor landslides. These findings have been furnished to the U.S. Coast Guard for issuance
as a Notice to Mariners, and to the National Ocean Survey of NOAA for bathymetric survey
planning. We also find that the flood plain boundary of the Mattole river at Petrolia will be
shifted by as much as 62 m as a result of the permanent change in elevation caused by the
earthquake (Stein, Marshall, and Murray).
Morphology of Slow-spreading Mid-oceanic Ridges Generated by Faulting. Fluctuations in magmatic activity at mid-oceanic ridges perturb the horizontal least principal stress across rift-bounding normal faults, leading to alternating phases of magmatic accretion, which increases valley width, and tectonic extension, which results in the growth of inner rift wall topography. Fine-scale bathymetric surveys and earthquake fault plane solutions show that active normal faults at slow-spreading ridges are moderately-dipping (approximately 45°) planar features throughout the seismogenic oceanic lithosphere. A simple quantitative model that includes flexural deformation of a 10-km-thick elastic plate by slippage on 45° dipping normal faults can match the bathymetric profiles across several slow-spreading ridge segments. Comparison among dip distributions of normal faulting earthquakes at mid-ocean ridges, in the trench-outer rise region, and on continents suggests that most events from these three tectonic environments initiated at dips close to 45°, raising unanswered questions about the mechanical conditions under which the faults originated (Thatcher and Hill).

REPORTS SUBMITTED OR PUBLISHED DURING THIS PERIOD (excluding abstracts):


Consolidated Digital Recording and Analysis

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Investigations.

The CUSP earthquake processing system is a computer-based integrated hardware/software system designed to record, process and archive the tens of thousands of earthquakes that occur in California every year. It was designed specifically for the large earthquake networks operated by the USGS (Menlo Park) in northern California and by a cooperative program between the USGS (Pasadena) and Caltech in southern California.

The CUSP system consists of three main components: (1) an online, real-time component that monitors earthquake activity within a network and captures events for further processing; (2) a relational database system that supervises the processing trail of each detected earthquake thru the system to the point of archiving and retrieving; and (3) an interactive graphics system for network personnel to visually process each earthquake. Each component can function on its own, in addition to being a part of an integrated system.

Hardware for these systems is based upon the Digital Equipment Corporation (DEC) VAX series of workstations. Currently, this includes the VAX microVAX II, VAXstations 2000, 3100 and 3200, and 4000 series. Software is based upon the DEC/VMS operating system, the CUSP database system, and the DEC/GKS graphics system.

Complete support for the CUSP system has been provided by four USGS persons: two each from Menlo Park and Pasadena. The following summary represents only the USGS (Menlo Park) CUSP support group, unless stated otherwise.

2. Results.

This project supports the Earthquake Hazards Reduction Program in the following ways.

2.1 Since 1984 the CUSP system has been used to process earthquakes at a rate of 10-20,000 per year in northern California (CALNET). The date for the southern California network is somewhat earlier.

2.2 In addition, the combined CUSP support group has provided installation and ongoing support for the following earthquake networks:
- Hawaii Volcanos Observatory, Hawaii
- Parkfield Prediction Experiment (Varian site)
- Parkfield Prediction Experiment (Haliburton site)
- University of Nevada (Reno)
- Idaho National Engineering Laboratories (INEL)
- University of Southern California
2.3 UC (Berkeley) Data Center:

Since April 1984 the CALNET project has been archiving its
digital waveform and related files (MEM files) to high-
density 9-track tapes. This year (FY 93) they began to
transmit all of the archived data to the UC Berkeley Data
Center. This project provided all of the software to the
Menlo Park end of this transfer project, and much of the
specialized software to the UC Berkeley end.

2.4 Operation and support of a computer-based earthquake network,
combined with the pressures of increasing requests for the data,
increasing requests for improvement of the quality of the data,
going requests to standardize the format for exchange of data,
going requests to merge network data, remarkable advances in
computer technology, and reductions in network funding and in
operational and support staff, have required us to be responsive.
Towards this end we have written much software, some of it a
"one shot" feasibility study, others of it have become part of
the daily operations repertoire or incorporated in the programs
of the research scientists who use the data.

A very small, but detailed, representation of some of this
software or other development follows.

2.4.1. Revised the cusp software directory tree structure.
Split into three sections: depict, generic, realtime. Allows
better maintenance of the code, by assigning responsibility for
the respective sections to independent software writers at
Pasadena and Menlo Park.

2.4.2. Installed and tested revised CUSP data acquisition software on
the main and backup acquisition systems in Menlo Park.

2.4.3. Developed code to archive CUSP .grm files to Exabyte tape.

2.4.4. Tested and implemented software to archive continuous digital
data from the online CUSP data acquisition systems. Digital
data buffers are dumped from computer memory into temporary
disk files (SQRL2DISK program); these files are later copied
to Exabyte tapes (PACKRAT program).

2.4.5 RTEXAM is a stand-alone program to monitor the "health" of the
real-time data acquisition system. Every 30 minutes it emerges
from a state of hibernation and answers the following questions:

1. Are all of the real-time computer processes running?
2. Are certain 'critical' disks becoming too full?
3. Is the real-time computer itself running?

Negative answers to any of these questions result in messages
being sent to persons on a pre-defined pager list.

Reports:

None.
Analysis of Growth Structures and Syntectonic Sedimentation: Implications for Timing, Slip Rates and Future Earthquakes along Buried Thrust Faults, Santa Barbara Channel

Program Element II.5

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Investigations Undertaken

Research undertaken in 1993 by the Princeton Structural Geology and Neotectonics Group has focused primarily on hazard analysis of major active blind thrust faults in the Santa Barbara Channel (Shaw, 1993; Shaw and Suppe, 1994; Mueller et al., 1994; Novoa et al., 1994). We have mapped active folds caused by displacement on non-planar blind thrusts along the Oakridge, Pitas Point, Blue Bottle and Dos Cuadras trends and their western extensions in the eastern Santa Barbara Channel. Map patterns derived by analysis of these growth structures (e.g., Suppe et al., 1992; Shaw and Suppe, in press) allow us to: 1) define the lateral distribution of dip slip along blind thrusts; 2) evaluate the recency of faulting and folding along them; 3) calculate their long-term slip rates and potential for future damaging earthquakes and, 4) complete kinematic analyses of their progressive development. Comparison of these growth structures with recent seismicity has also revealed important relations between active folding and microseismicity (Shaw, 1993).

Results

Southeastern Channel Region: Axial surface mapping, balanced cross section construction and kinematic analysis of fault related folds along the Pitas Point and Blue Bottle trends have constrained the location and geometry of a south vergent thrust system contained above the north-dipping Channel Islands Thrust (Figure 1; Shaw, 1993). Analysis of syntectonic (growth) sediments yields a combined Quaternary slip rate of 1.3 mm/yr on the thrust system (Pitas Pt and Montalvo blind thrusts; Shaw, 1993; Shaw and Suppe, in press). The coincidence of active axial surfaces developed above these thrusts with the bathymetric expression of the active folds on the seafloor show that these faults are active and pose a seismic risk to the region. Comparison of the 1984 Santa Barbara Channel earthquake swarm (Henyey and Teng, 1985) with growth structure associated with the Channel Islands thrust show that small scale faulting is a dominant deformation mechanism associated with active fault bend folding (Figure 2; Shaw, 1993). In addition, the Channel Islands thrust is the dominant blind thrust in the Santa Barbara Channel; maximum future earthquakes likely to occur along it may have M = 7.2 to 7.3.

Northeastern Channel Region: We have expanded our work to the northern Channel and Santa Ynez Mountains, because the highest deformation rates exist here. Balanced cross section construction and kinematic analysis of thrust faults and fault related folds along the Dos Cuadras trend were completed using a grid of oil industry seismic reflection profiles and well data. (Figure 1). Results of this work suggest a complex pattern of north and south vergent thrust faulting and fault bend folding, dominated by wedge structures. The timing of development and geometry of these structures determined by application of growth fold theory suggests a link between blind wedge structures beneath the Dos Cuadras trend and the active, north-vergent Red Mountain and Rincon Creek thrusts (Jackson and Yeats, 1982). Other active blind thrust faults mapped in this region include the Santa Ynez thrust (new name - Novoa et al., 1994), a south vergent, blind thrust displaying approximately 20 km of shortening. Integration of historic
Figure 1. A balanced, retrodeformable cross section across the offshore Oakridge, Blue Bottle, Pitas Pt and Dos Cuadras trends that combines subsurface seismic reflection and well log data (note trace of section on Figure 2). Note the different levels of blind thrust faulting. Section adapted from Shaw, 1993 and Novoa, unpublished mapping.
Figure 2: Epicenters from an earthquake swarm in 1984 (Henyey and Teng, 1985) define the active axial surface (A) of the Offshore Oak Ridge trend. Single event (C, D) and composite (E, F) focal mechanism solutions from the 1984 seismicity show gentle north dipping (C, D, E) and horizontal (F) preferred nodal planes (Henyey and Teng, 1985) consistent with folding through the active axial surfaces by bedding parallel slip. Note the location of the cross section line shown as Figure 1.
seismicity data indicates that the 1978 Ml 5.1 Santa Barbara earthquake occurred along a ramp segment of the Santa Ynez blind thrust.

**Western Santa Barbara Channel:** Preliminary mapping in the Western Santa Barbara Channel using 135 newly acquired seismic reflection profiles indicates that the Channel Islands Thrust (Shaw, 1993; Shaw et al., 1994; Mueller, et al., 1994) extends westward to at least midway between the longitudes of the city of Santa Barbara and Point Conception. Additional mapping of axial surfaces in the western Santa Barbara Channel has defined the location of an active, structurally higher, south vergent thrust fault. This fault extends completely across the western channel to Point Conception and may be the westward continuation of a thrust fault located beneath the Blue Bottle trend to the east (Shaw, 1992; Shaw and Suppe, 1994). In addition a dip panel associated with the preexisting Channel Islands Thrust limits the updip extent of the ramp developed in the active, structurally overlying thrust, effectively controlling the maximum size of future earthquakes along it.

**Arc/Info data base:** We have input shot point locations of over 220 seismic reflection profiles from 6 separate industry surveys located throughout the Santa Barbara Channel into the Arc/Info format. This, combined with the development of a spreadsheet database has allowed us to accurately record the results of out axial surface mapping of fault related folds. We have also downloaded the entire USGS/CIT data base of instrumented earthquake locations and magnitudes in this region for comparison with the mapped location of active seismicity. In the upcoming year we will continue to integrate our ongoing mapping with recent seismicity, high-resolution bathymetry and newly acquired seismic reflection data (Sparker and Uniboom).

**Future work**

Upcoming work will focus on further defining the rates of blind thrust faulting and fault related folding in the Santa Barbara Channel. We are currently extending our existing balanced cross sections in the western Channel region onto the northern shelf and onland to evaluate the kinematic evolution and timing of crustal shortening across the entire Western Transverse Ranges. We will also be conducting a high resolution seismic reflection survey (Sparker and Uni-Boom) this winter in the north-central and western Santa Barbara Channel to evaluate the likelihood of determining Late Quaternary coseismic folding events. We will focus acquisition along active axial surfaces associated with the Channel Islands thrust in an attempt to constrain the record of late Quaternary blind thrusting along it. In addition, we will be continuing to map growth structure associated with active blind thrust faults on 135 newly acquired seismic reflection profiles located between Santa Barbara and Pt. Conception.

**References**


Reports Published


INFLUENCE OF THE SOUTHERN WASHINGTON CASCADES CONDUCTOR
ON VOLCANISM AND TECTONISM

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Investigations

The Hamilton Buttes 7-1/2-minute quadrangle (fig. 1), near the eastern edge of the Southern Washington Cascades Conductor (SWCC; Stanley and others, 1987, 1990, 1992), was mapped geologically at a scale of 1:24,000. In addition, parts of the Tower Rock (Swanson, 1991), McCoy Peak (Swanson, 1992), French Butte (Swanson, 1989), Greenhorn Buttes (Swanson, 1989), Blue Lake (Swanson, 1993), and East Canyon Ridge (Swanson, 1994) quadrangles were field checked and modified where necessary. The northern part of the Green Mountain quadrangle was mostly completed; the Quaternary rocks are included in a map currently in press (Hildreth and Fierstein, in press), so I am concentrating on the small exposures of Tertiary rocks. In addition, the southern part of the Randle quadrangle was completed and will be incorporated into a map that Dick Moore (Branch of Volcanic and Geothermal Processes, U.S. Geological Survey, Denver) is preparing for open-file release in early 1994. The geologic map of the Hamilton Buttes quadrangle will be released as an open-file report after chemical analyses and thin sections are received and evaluated, most likely in 1994.

This work is part of an ongoing cooperative effort with Roger Ashley and Russ Evarts (Branch of Western Mineral Resources, U.S. Geological Survey, Menlo Park) and R.B. Moore to define the development of the Cascade Range along an east-west research corridor in the Mount St. Helens area (fig. 1). The SWCC, an anomalous electrical conductor at intermediate depth within the crust, underlies that part of the research corridor between Mount St. Helens and Mount Adams. One goal of the cooperative effort is to compare and contrast volcanism and tectonism above the SWCC with that beyond the limits of the SWCC.

Improved understanding of the nature and influence of the SWCC is important in order to define and evaluate earthquake hazards in the area. The western margin of the SWCC coincides with the St. Helens seismic zone (Weaver and Smith, 1983; Grant and others, 1984; Grant and Weaver, 1986), which “could, under certain assumptions, be capable of generating a magnitude 7.0 earthquake” (Weaver and Smith, 1983, p. 10,380). The northeastern margin of the SWCC includes a north-northwest-trending zone of seismicity near Mount Rainier (Weaver and Malone, 1987; Stanley and others, 1987) and the epicentral area of the 1981 Goat Rocks earthquake (magnitude 5.0; Zollweg and Crosson, 1981; Weaver and Smith, 1983). The Hamilton Buttes quadrangle includes part of the Goat Rocks Wilderness, near the location of the 1981 Goat Rocks earthquake.

Five days were devoted to paleomagnetic sampling of selected volcanic and intrusive rocks, in a combined effort with Jon Hagstrum and Duane Champion (Branch of Isotope Geology, U.S. Geological Survey, Menlo Park). Forty sites, with approximately 400 cores, were studied for the purposes of assessing the relative ages of folding and dike intrusion in the area and to evaluate further the amount of tectonic rotation these Tertiary rocks have experienced.
Russ Evarts and I logged the field trip across the area that we will be leading for the Annual Meeting of the Geological Society of American in Seattle in October 1994 (Evarts and Swanson, 1994).

**Results**

The Hamilton Buttes quadrangle contains a suite of volcanic rocks ranging in age from latest Eocene or earliest Oligocene (about 36.0 Ma, based on a zircon fission-track age) to Quaternary (probably late Pleistocene). Fluvial volcanic sandstone and diamictite (mostly of lahar origin) dominate the 3–km-thick Tertiary section exposed in the quadrangle; andesitic and basaltic andesitic lava flows, andesitic and dacitic pyroclastic flows, and minor dacitic and rhyolitic lava flows and domes, are locally present. The lower 1–1.3 km of the volcanic section overlie and are interbedded with fluvial arkose derived from erosion of pre-Tertiary rocks in northeastern Washington (Winters, 1984). To accommodate such a thick interbedded section of fluvial arkose and volcaniclastic rocks, ongoing subsidence during deposition seems likely and almost demanded. Hence the early history of the Cascade arc in this area can be interpreted as one of active subsidence, not uplift as took place in the Neogene. What caused the subsidence—extension, compression resulting in a syncline, or some transtensional or transpressional regime—remains to be worked out.

These rocks were intruded by numerous andesitic and microdioritic sills and then folded along a north-northwest-trending anticline (the Johnson Creek anticline) that diagonally crosses the eastern part of the quadrangle. The arkose and lower part of the volcanic section is exposed in the axial part of the anticline. Dips on the flank of the anticline are as high as 50°, and the fold has a structural amplitude of at least 3 km.

The folding probably took place before about 12 Ma, the approximate age (from zircon fission-track counts) of a suite (the Kidd Creek suite of Marso and Swanson, 1992) of hornblende andesite-dacite and hornblende diorite-quartz diorite dikes and sills that intrude the section farther west. This hornblende-bearing suite forms a subvolcanic complex with a large radial dike swarm (Swanson, 1990, 1991) centered in the northeast part of the McCoy Peak quadrangle. The pattern of the radial dikes, and their systematic subvertical orientation, indicate that they were intruded after folding, which produced dips of 30–50° (in places, possibly disturbed by faulting, even 85°). The paleomagnetic sampling done this year will further test whether the dikes have been folded.

The distribution of the Kidd Creek intrusive suite is of interest relative to the eastern limit of the SWCC. From previous reconnaissance work, the suite was thought to occur only a little farther east than the eastern edge of the Blue Lake and East Canyon Ridge quadrangles, which roughly coincides with the margin of the SWCC (figs. 1 and 2). This year’s work confirmed this distribution; the Kidd Creek intrusive suite occurs only in the extreme southwest corner of the Hamilton Buttes quadrangle and the extreme northwest corner of the Green Mountain quadrangle. Consequently the Kidd Creek is virtually confined to the geophysically defined SWCC.

Quaternary lava flows of andesite and basalt unconformably overlie the folded Tertiary rocks. These flows were erupted from vents in the Goat Rocks Wilderness and just south of the wilderness along the crest of the Cascades. Thick valley-filling flows, of probable late Pleistocene age, from the Goat Rocks dammed Walupt Creek to form Walupt Lake, just east of the Hamilton Buttes quadrangle. Basalt and andesite flows from the Mount Adams volcanic field cover large parts of the Green Mountain quadrangle (Hildreth and Fierstein, in press).

No evidence of active faulting was found in the Hamilton Buttes and northern part of the Green Mountain quadrangles. However, many small shear zones, generally north-northwest striking, cut the Tertiary rocks. These shears typically have indicators of dextral slip (subhorizontal slickensides on appropriately stepped surfaces). None of these shears has been found cutting Quaternary lava flows. The northwest to north-northwest strike of most of the shears is similar to that of the fold axes in the mapped quadrangles. Perhaps both can be accounted for in a transpressional setting.
Large landslides are common and were generally shed from steep dip slopes on the west flank of the Johnson Creek anticline. One lake (Wobbly Lake) and several marshes formed as a result of slides. Wobbly Lake was dammed by a large debris avalanche. Bob Schuster (Branch of Geologic Risk Assessment, U.S. Geological Survey, Denver) and I looked at Wobbly Lake for drowned trees for possible dating but found none. Schuster has one age from nearby landslide-dammed Packwood Lake that suggests temporal correlation with earthquakes that affected the Puget Sound area (Schuster and others, 1992). Next year Pat Pringle (State of Washington) and I plan several auger holes at Wobbly and nearby marshes to use Mount St. Helens ash deposits to bracket the age of sliding. We suspect that these slides may have been triggered by earthquakes and need ages to test this hypothesis.

To summarize, work in the Hamilton Buttes and adjacent quadrangles has found several features unusual for the southern Washington Cascades that may reflect the presence of the SWCC. The two most intriguing are an extensive hornblende-bearing suite of intrusive rocks and the possible control by the SWCC on the distribution of this suite. Dextral shear is pervasive throughout all of the quadrangles mapped, though not of notable magnitude along individual shears, and may together with the folds indicate a transpressional regime. Numerous landslides could have been triggered by earthquakes. Continued study of the several quadrangles already completed, and of those targeted for future work, will address these issues.

Reports


References Cited


Figure 1. Map showing locations of Hamilton Buttes quadrangle and other quadrangles being mapped in the southern Washington Cascades relative to the Southern Washington Cascades Conductor (SWCC). The quadrangles west of longitude 122° are being mapped by Russ Evarts and Roger Ashley (U.S. Geological Survey, Menlo Park), and those east of longitude 122° by me.
Figure 2. Generalized geologic map of the Hamilton Buttes quadrangle, showing relations among the Tertiary volcanic and volcaniclastic rocks, arkose, and Quaternary basalt and andesite. Note concentration of sills in the interlayered, well-bedded section of volcanic sandstone, mudstone, and micaceous arkose in the core of the Johnson Creek anticline. Note also the small sill of hornblende microdiorite of the Kidd Creek intrusive suite in southwest corner of quadrangle, the farthest northwest occurrence of the Kidd Creek and almost exactly along the eastern edge of the SWCC (fig. 1) as mapped by Stanley and others (1987).
Intermediate and Long-term Seismic Precursors to Large Earthquakes in California
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Objective:

For the past several years we have been studying premonitory changes before large earthquakes along the San Andreas fault system in California. Moderate earthquakes prior to the 1868 Hayward, 1906 San Francisco, and 1989 Loma Prieta earthquakes in central California, most or all of which are outside the ensuing rupture zone, show a pattern of accelerating moment release. In light of this precursory change in seismicity in a region of complex fault interaction, we have begun re-examining seismicity of moderate-to-large earthquakes in southern California to establish if such changes also occur before large earthquakes on the San Andreas system in southern California. We have also examined changes in the occurrence of moderate earthquakes in the San Francisco Bay region in the context of stress changes generated by the occurrence of the large earthquakes of 1868 and 1989, and the great 1906 earthquake. We find that M ≥ 5.5 earthquakes in the few tens of years before 1906 and 1989 preferentially occur in regions expected to be more highly stressed before those earthquakes, and the moderate earthquakes after 1906 and 1989 occur in regions moved towards failure by coseismic stress changes.

Results:

The rate of seismic activity of moderate-size (M ≥ 5.5) earthquakes in the San Francisco (SFB) region has varied considerably during the past 150 years. As measured by the rate of seismic moment release, seismic activity in the SFB region is observed to accelerate prior to M ≥ 7.0 earthquakes in 1868, 1906, and 1989, and then decelerate following them. We examine these seismicity changes in the context of stress changes in the SFB region by modeling the M ≥ 7.0 earthquakes as dislocations in an elastic
halfspace and calculating the changes in the tensor stress field associated with the accumulation and release of strain in the earthquakes of 1868, 1906, and 1989. We use a Coulomb Failure Function (CFF) to take into account changes in both shear and normal stresses on potential failure planes of varying strike and dip in the SFB region. The moderate-size earthquakes during the decades immediately preceding the M \geq 7.0 earthquakes fall in regions that are calculated to have had 0.01 MPa or greater stress changes during the period of strain accumulation for the large and great shocks, consistent with the observation that the size of these regions scale with the size of the oncoming earthquake. The decrease in seismicity throughout most of the SFB region and a localized increase in seismicity in the Monterey Bay region following the great 1906 earthquake is consistent with the predicted stress changes, which, depending on fault orientation and assumed coefficient of friction, tend to drive faults in the Monterey Bay region towards failure. The 1911 earthquake southeast of San José is also consistent with the predicted stress changes, but only if it occurred on a reverse fault, and not on the Calaveras fault as previously hypothesized. We also find that the spatial distribution of M \geq 5.5 earthquakes in the years 1955-1989 is more consistent with an oncoming M \geq 7.0 earthquake along the Loma Prieta segment of the San Andreas fault than on either the Peninsular segment of the San Andreas fault or the southern Hayward fault. Much of the moderate-size earthquake activity in the SFB region appears to be modulated in time by the buildup and release of stress in large and great earthquakes. A tensorial approach to earthquakes prediction, i.e. taking into account changes in the components of the stress tensor, has several advantages over examining scalar changes such as those in seismic activity and moment release rates. This tensorial approach allows for both activation and quiescence (but in different subregions) prior to as well as after large earthquakes.

In a paper published in Science "Changes in State of Stress on the Southern San Andreas Fault Resulting from the California Earthquake Sequence of April to June 1992" Jaumé and Sykes (1992a) modelled stress changes on the southern San Andreas and northern San Jacinto faults caused by the occurrence of the Landers, Joshua Tree and Big Bear earthquakes of 1992. Jaumé and Sykes (1992b) presented updated calculations of that type at an invited session of talks at the AGU meeting in December 1992. We calculated changes in shear stress and in the Coulomb Failure Function, CFF. A 50-km section of the San Andreas fault in the San Gorgonio Pass area was moved significantly closer to failure by stress
changes induced by the 1992 earthquake sequence. Stress changes on other segments of the San Andreas fault were smaller, with the Coachella Valley segment being moved closer to failure and the Mojave and northernmost San Bernadino segments being moved away from failure.

We also considered changes in pore fluid pressure caused by changes in normal stress across the San Andreas at the time of the 1992 sequence. Initially about 60% of the decrease in total normal stress is taken up by a drop in fluid pressure in the fault zone at depth and only 40% goes into a drop in effective normal stress. The initial change in CFF is modelled by a low value, 0.3, of the effective coefficient of friction, $\mu$. As fluid pressure along the San Andreas fault returns to its pre-Landers value with time, the effective normal stress decreases further and CFF increases. We conclude that the San Andreas fault in San Gorgonio Pass moved closer to failure at the time of the 1992 sequence by a maximum $\Delta$CFF = 0.5 MPa (5 bars) whereas with time and increasing fluid pressure $\Delta$CFF should increase by an additional 3 bars to a total of about 8 bars (0.8 MPa).

Two results are very important -- 1) the San Andreas fault moved significantly closer to failure in 1992 and should move even closer to failure as fluid pressures re-equilibrate with time. The time constant for fluid diffusion is poorly known but appears to be in the range of 1 to 10 years based on earthquakes like Koyna that were triggered by fluid pressure being communicated to the hypocenter along a fault zone following the filling of a large reservoir. We believe the Landers sequence increases the probability of a great earthquake along the southern San Andreas fault since the repeat time of Landers earthquakes is much longer than of great events along the San Andreas. Landers should not be thought of as being part of the normal build up to great events along the San Andreas.

Reports Published:


Nearfield Geodetic Investigations of Strain across Faults in Southern California

1434-93-G2290
Program Element II.3
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INVESTIGATIONS

The long-term, fixed purpose of this investigation is to search for and monitor the spatial and temporal nature of nearfield displacement across active and potentially active faults. Thus, we document pre-, co- and post-seismic displacement and aseismic creep, if any, especially where seismographic, paleoseismic, and geomorphic evidence indicates current or recent fault activity. The geodetic arrays range in length from 300 m to 7000 m and are intermediate in scale, therefore, between the infrequent, regional geodetic surveys traditionally done by the National Geodetic Survey, and point measurements by continually recording instruments such as creepmeters, tiltmeters, and strainmeters. All leveling is done according to First Order, Class II standards, and horizontal surveys are done to First Order standards.

We concentrated on three main tasks during 1993: 1) resurvey of all of our trilateration arrays established across surface ruptures related to the 28 June 1992 Landers earthquake (M=7.3) to search for continued afterslip; 2) resurvey of all leveling lines in the creeping segment of the San Andreas fault between San Juan Bautista and Cholame to prepare a summary of creep activity for much of the time of the forecasted Parkfield earthquake; and 3) resurvey of all leveling lines in Coachella Valley to monitor effects of the Landers earthquake on this seismically critical area.

RESULTS

1. We have observed no afterslip during 1993 within any of our arrays across the surface ruptures of the Landers earthquake (Sylvester, 1993), except in the array across the Burnt Mountain fault, south of Yucca Valley. That array has accumulated nearly 45 mm of afterslip in the time from five days after the earthquake to the middle of summer 1993.

2. We releveled seven sites across the San Andreas fault in the creeping segment between Gold Hill in Cholame Valley and San Juan Bautista to compare with our previous data, some stretching back 18 years, and to compare with horizontal creep data from USGS creepmeters. Leveling lines of permanent benchmarks are from 0.9 km (San Juan Bautista) to 7 km (Gold Hill) long. Precision of leveling ranges from 0.5 to 1 ppm. Nearby creepmeters with apertures from 10 m to 30 m measure horizontal displacement to fractions of a millimeter. Displacements and time averaged slip rates, from northwest to southeast along the fault, are (Sylvester and Breckenridge, 1993):

<table>
<thead>
<tr>
<th>Site</th>
<th>Epoch</th>
<th>Horiz. mm</th>
<th>Avg/yr mm</th>
<th>Vert. mm</th>
<th>Avg/yr mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Juan Bautista</td>
<td>1975-93</td>
<td>129</td>
<td>7.2</td>
<td>70</td>
<td>3.9</td>
</tr>
<tr>
<td>Lewis Creek</td>
<td>1985-93</td>
<td>120</td>
<td>14.9</td>
<td>19</td>
<td>2.4</td>
</tr>
<tr>
<td>Mustang Grade</td>
<td>1985-93</td>
<td>120</td>
<td>15.0</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Parkfield</td>
<td>1980-93</td>
<td>113</td>
<td>8.7</td>
<td>15</td>
<td>1.2</td>
</tr>
<tr>
<td>Car Hill</td>
<td>1987-93</td>
<td>41</td>
<td>6.9</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>Turkey Flat</td>
<td>1987-93</td>
<td>41</td>
<td>6.9</td>
<td>11</td>
<td>1.8</td>
</tr>
<tr>
<td>Gold Hill</td>
<td>1987-93</td>
<td>27</td>
<td>4.5</td>
<td>33</td>
<td>5.5</td>
</tr>
</tbody>
</table>
The large height changes at San Juan Bautista, Parkfield, and Gold Hill may be related to nontectonic subsidence where groundwater is pumped from unmonitored irrigation wells on one side of the fault. At San Juan Bautista, however, the water table has remained nearly constant according to local farmers, even though the height change there is the greatest among the seven sites. Horizontal creep is greatest and fastest in the center of the creeping segment (Lewis Creek and Mustang Grade), whereas vertical creep is greatest at the extremities of the creep zone (San Juan Bautista and Gold Hill). Most of the vertical displacement occurs at the surficial trace of the fault. Downwarping is evident as much as 500 m from the mapped fault trace, however, consistent with conclusions of other workers that surficial creep is a shallow phenomenon, limited to the upper 0.5 km to 1 m of the crust. Earthquake precursors are not present in the vertical data, yet the horizontal creep rate clearly increases after local earthquakes, especially at San Juan Bautista where it has doubled or trebled after earthquakes greater than M 4.5 (Behr, Bilham, Bodin, Breckenridge, and Sylvester, in press).

3. Before the Landers earthquake, Durmid Hill at the southeasternmost end of the San Andreas fault, rose more or less continuously at a rate of 1-2 mm/yr relative to one of the end points (Sylvester, Bilham, Jackson, and Barrientos, 1993). We have leveled the line twice (4.2 km long) since the earthquake and have found that the uplift has ceased. Because Durmid Hill is located at the juncture of the Brawley seismic zone with one of the most dormant parts of the San Andreas fault anywhere along its entire length, we are concerned that the hill’s behavior change may be tectonically significant, so we have focused our attention on it and neighboring arrays in the Coachella Valley. Thus, during the reporting period, we have releveled BAT CAVES, NORTH SHORE, CORVINA BEACH twice, and BOX CANYON, PAINTED CANYON, THOUSAND PALMS, MIRACLE HILL, MORONGO WASH, and WHITewater once each. No height changes occurred in the level lines since March 1992. That means that the southern San Andreas segment was not perturbed by the Landers earthquake, at least within the limits of detection by our methods (± 2 mm horizontal; ± 0.5 mm/km vertical), except the BAT CAVES line across Durmid Hill. There the lack of change since March 1992 contrasts with the aseismic uplift observed for periods of 8, 300, 10,000, and 730,000 years beforehand (Sylvester, Bilham, Jackson, and Barrientos, 1993).

REPORTS PUBLISHED


The aforementioned report presents location and measurement information for all nearfield leveling, trilateration, and nail line arrays currently surveyed by this activity. Copies may be obtained from the author at no cost upon request.
Investigations

The 10/17/89 Loma Prieta earthquake caused widespread ground failure in the alluvial, estuarine, littoral and eolian deposits surrounding Monterey Bay. The distribution of ground failures affords an opportunity to conduct detailed field and laboratory studies of ground failure in a well-documented regional geologic setting. To date, 14 sites where ground failure occurred and 4 sites where ground failure did not occur have been explored using geologic and geotechnical methods. The research offers strong prospects for improved understanding of liquefaction-related ground failure and the preparation of improved liquefaction maps, and for testing empirical methods for predicting liquefaction-related ground displacements commonly used in standard engineering practice.

The 1989 earthquake effectively tested the regional geologic and liquefaction susceptibility maps of the Monterey Bay area published by Dupré and Tinsley (1980). A principal goal of the study is to develop improved criteria for making regional liquefaction hazard maps, enabling them to be as precise and as quantitative as possible. Ideally, a new generation of liquefaction hazard maps to forecast not merely the location but also the relative severity of the effects of ground failure. This research is an important component of interrelated studies funded by the Office of Earthquake Studies and the Office of Regional Geology. See also a report of liquefaction studies by Thomas Holzer and others, this volume).

The overall approach embraces (1) theoretical and empirical studies of ground motion attenuation relations as well as documented historical ground failures owing to liquefaction in the Monterey Bay area, supported by in-situ geologic and geotechnical studies comparing and contrasting failed and unfailed sites; (2) evaluations of mapping criteria commonly employed in order to distinguish depositional facies of geologic deposits susceptible to liquefaction from deposits not susceptible to liquefaction; (3) using GIS-based statistical studies evaluate ground failure distribution on an areal basis and on a site-specific basis relative to the index properties of soils comprising the key geologic map units that sustained ground failure.

Results

The liquefaction-related ground failures in the Monterey Bay region show that regional surficial geologic mapping can be used successfully to forecast the general location of future ground failures. For example, 47 lateral spread ground failures were mapped during post-earthquake investigations in the Monterey Bay area; 46 of these occurred in areas identified by the Dupré and Tinsley (1980) as having high or very high susceptibility to liquefaction. The Dupré and Tinsley mapping was produced using the methodology of Youd and others (1975) as detailed further by Youd and Perkins (1978). Thus, the 10/17/89 earthquake provided the
Program Element II

first objective test of regional hazard mapping of liquefaction-related ground failures, and a successful test of the Youd and Perkins' approach.

Laboratory work is completed on more than 350 geotechnical samples obtained from during FY 1991-1993, including Standard Penetrometer Testing, grain-size distribution, Atterberg limits, moisture content, radiometric dating and stratigraphic description of samples taken during 1989-1993; these data have been installed into a geotechnical database management system (GTGS) and are being compiled for release to data repositories selected to contain data gathered from the 10/17/89 earthquake.

Six digital maps (1:24,000) showing the surficial geology of the Monterey Bay area as mapped by Dupré and Tinsley (1980) were prepared from scanned maps, then were edited and compiled into one sheet at a scale of 1:62,500 using ArcInfo software. Overlays showing the distribution and character of liquefaction-related ground failures at a scale of 1:62500 are compiled from field maps. From these basic data, GIS techniques have been used to make maps estimating the relative susceptibility to lateral-spread ground failures in natural deposits in the Monterey Bay area of central California from a multiple-linear (probit) regression. Five variables (geologic age, sand content, horizontal distance to nearest free-face or surface water, terrain elevation, and slope) were used to estimate the relative likelihood that one of 75,000 1-hectare square parcels is in a geologic unit likely to liquefy. Efforts are continuing in order to refine the techniques and transfer them to other areas such as the southern Santa Clara valley.

Radiocarbon samples submitted in 1990-1992 for dating using accelerator mass-spectrometer techniques support the paradigm that the region's youngest cohesionless deposits (those that are historical or just a few hundred years old) have the greatest susceptibility to liquefaction, a trait noted by Youd and Perkins (1978) and exploited by Dupré and Tinsley (1980) and Tinsley and others (1985) in published liquefaction potential mapping in the Monterey Bay area and in the Los Angeles region.

The location of lateral-spread ground failures and other sites of liquefaction manifest by sand-boil activity during the Loma Prieta earthquake were chiefly restricted to laterally accreted depositional facies, with special emphasis on point-bar facies (a heretofore not well-recognized finding) along the lower meandering reaches of the coastal streams. The Salinas, Pajaro, and San Lorenzo rivers in the Monterey Bay area, a coastal setting wherein response by rivers to stable or slowly rising Holocene sea levels relative to the land has been the deposition of locally extensive areas of point-bar, levee, and channel deposits bounded by vertically accreted floodbasin and floodplain deposits. The vertically accreted fluvial facies were effectively immune to lateral spreading ground failure and lateral spread ground failure during the 1989 earthquake, in stark contrast to marked lateral displacements and vertical deformational effects mapped in the laterally-accreted fluvial facies following the 10/17/89 earthquake.

Facies analysis of zones of failure continues in the coastal zone, where a complex interplay of longshore bars, eolian dune deposits, and historical changes in the location of rivers and bay mouths make a more complicated stratigraphic picture compared to the purely fluvial setting.

See report by Holzer and others, this volume, for additional information concerning USGS liquefaction research.
References cited


Reports:


INVESTIGATIONS:

In 1991, we collected seismic refraction/wide-angle reflection data along several profiles in Oregon and Washington in collaboration with other scientists from the US Geological Survey, the Geological Survey of Canada, the University of Texas at El Paso, and the University of Wyoming. The objectives of this project were to image along-strike variations in the crustal structure of the Cascadia subduction zone and to tie the onshore structure with to results obtained from a 1989 NSF-funded onshore-offshore crustal imaging program on the Oregon continental margin. Effort in FY93 focussed on finalizing modeling of the data, preparing the data for general distribution, and presenting the data processing and modeling results for publication.

RESULTS:

In order to obtain additional constraints on the potential seismic hazard associated with Cascadia, we conducted a series of active seismic experiments in 1989 and 1991 to image the crustal architecture of the forearc. The 1989 experiment (funded by NSF) comprised a multichannel seismic-reflection profile using a large-volume tuned airgun source and long streamer which extended from the abyssal plain to the coast. The airgun shots were also recorded by ocean-bottom and onshore seismometers to provide complementary large-aperture data. In 1991, this study was extended into the foothills of the Cascades using several hundred seismometers and large explosive shots onshore. Figure 1 shows the location of the experiments overlain on a simplified regional geology map. The dashed line shows a multichannel seismic profile comprising approximately 1000 shots from a tuned airgun array, which were also recorded on 6 Ocean Bottom Seismometers and 10 onshore seismometers (dots); the solid lines shows three profiles, comprising 450-600 seismometers each (1991), that recorded signals from 27 large explosive shots. We have concentrated on the east-west transect extending from the abyssal plain seaward of the deformation front, across the continent margin, Coast Range, Willamette Valley, and into the foothills of the Cascade mountains and the north-south profile extending along the boundary between the Willamette Valley and the Oregon Coast Range and into the Coast Range of southwest Washington. The basement rocks throughout most of this region are generally thought to be Paleocene to early Eocene oceanic crust and seamounts that outcrop in numerous places in the Coast Range.
Figure 2a shows a velocity model for the NS profile in Oregon derived from analysis of travel times of diving waves and wide-angle reflections using a hybrid forward/inverse modeling approach based on the method of Zelt and Smith (1992) and discussed in detail by Trehu (in preparation). An example of the fit of the model to the data is shown in figure 3a. The rms misfit of the model to the observed travel times for all shot points is 0.10s. Large lateral velocity variations in the upper 2.5 km correlate well with sedimentary basins and basement uplifts and indicate that the basins are quite shallow and underlain by the same high velocity rocks that comprise the basement uplifts. Basement velocities increase rapidly with depth, reaching a velocity of 6.5 km/s at depth 11 km depth south of km 175 and at 7 km depth north of km 125. Beneath these depths, the gradient decreases significantly, reaching a velocity of about 7.0 km/s at about 25 km depth, which represents the maximum depth imaged by first arrivals in spite of the maximum recorded offset of 350 km.

Information on the total crustal thickness and on the velocity structure of the lower crust is obtained only from wide angle reflections that are observed as secondary arrivals and assumed to be PmP. Large differences in the amplitude behavior of these wide angle reflections as a function of shot-receiver offset indicate that the velocity of the lower crust is variable along the profile but falls between 6.5 km/s and 7.2 km/s. Inversion of the observed travel times of the wide-angle reflections for several possible lower crustal velocity indicates a total crustal thickness of 45-50 km beneath the central 150 km of the profile.

The velocity model for the NS profile suggests a much thicker crust beneath western Oregon than was included in many earlier models of western Oregon, which show a 17 km thick crust in this region. The velocity structure of the upper 25 km is very similar to the velocity structure of oceanic plateaus, such as the Ontong Java Plateau, which are thought to be the marine equivalent of continental flood basalts. Based on several studies that show that the thickness of the oceanic layer 2 (as defined by velocities < 6.5 km/s) increases as the total crustal thickness increases for both normal and overthickened oceanic crust, we tentatively interpret the northward increase in upper crustal velocity to indicate northward thinning of the crust of the Siletz terrane. The thickness of this accreted, early Eocene-aged terrane in western Oregon may explain why it has behaved as a coherent block since docking against the north American continent, whereas its counterpart in western Washington has behaved as a string of disconnected blocks that have rotated relative to each other and appear to be separated by electrically conductive channels and zones of increased seismicity.

Figure 2b shows the velocity model for the EW profile obtained from travel time analysis overlain by a geologic interpretation. An example of the fit to the data is in figure 3b. Our modeling approach was similar to that used for the NS profile. In addition, shallow basin structure and the top of the oceanic crust in this model were constrained by the coincident MCS profile. The overall rms misfit of the model to some 3000 data points is 0.18 s. This image contrasts significantly with several recently published summaries of crustal structure of western Oregon that were based on old seismic data and gravity modeling, but is remarkably consistent with the coincident electrical conductivity model determined during EMSLAB.

A well-defined deformation front observed in the sediments near km 30 marks the beginning of the Cascadia subduction zone. Between km 30 and km 100 is a zone of highly deformed sediments comprising the accretionary prism. Although the subducted oceanic crust cannot be traced more than 30 km east of the deformation front in the multichannel reflection data, the large-aperture data require that it underplate the entire continental margin. Our inability to image the subducted crust beneath continental slope in the MCS data is probably due to scattering because of the presence of considerable gas in the accretionary prism sediments combined with a complicated structure comprising large
blocks of upper oceanic crust in a sedimentary matrix (analogous to the Franciscan terrane of western California).

A 5-km-thick basin, underlain by a block-faulted basement surface that represents the top of the Siletz terrane, is found on the continental shelf. The sediments in this basin record a complicated Neogene history of folding, faulting, uplift, subsidence, and intrusion. Understanding this history has been hindered by the unknown configuration of the subbasement structure. Our data reveal that the Siletz terrane is at least 10 km thick beneath the shelf and forms a nearly vertical subduction backstop, as indicated by the abrupt eastward increase in crustal velocity near km 105. A subhorizontal reflection beneath the shelf originates at a depth of about 17 km and reflects either the base of the Siletz or the top of subducting oceanic crust. In the absence of large-aperture data, this reflection would probably have been interpreted as Moho, yielding an estimate of crustal thickness that was consistent with earlier studies. Wide angle reflections from the base of the crust recorded on onshore stations from offshore shots, however, indicate that the crustal thickness increases from about 22 km at km 105 to 30 km beneath the coast.

Onshore, the data indicate that the 2 km thick layer of low velocity material associated with the Willamette Valley extends about 30 km east of the surface occurrence of Cascade volcanic rocks, suggesting that the Cascades were erupted over a well-developed sedimentary basin. Material with a velocity appropriate for Siletz basement underlies the entire basin. Because the high velocity material at the eastern end of the profile probably corresponds to a local intrusion rather than to a major terrane boundary, our model indicates only a minimum eastward extent of the Siletz terrane.

The structure of the lower crust and upper mantle onshore are constrained by several fan shots recorded at offsets of 90-220 km, by the north-south profile, and by a new image of the lower crust and upper mantle from the coast to the back-arc derived from teleseismic receiver functions (Nabelek et al., 1993). The north-south profile requires that the Juan de Fuca plate underplate the crust of the North American at least as far east as the western Willamette Valley. The fan and receiver function array data indicate that the base of the North American crust is at approximately 30 km depth beneath the Cascades and eastern Willamette Valley and that the Juan de Fuca plate plunges into the mantle beneath the Willamette Valley, thus defining the geometry of the wedge of North American mantle that underlies the Cascades.

This image of the Cascadia forearc in Oregon contrasts significantly with a similarly well-resolved image of the Cascadia subduction zone further north offshore Vancouver Island obtained by the Geological Survey of Canada and the University of British Columbia (figure 4a). The crustal velocity and thickness beneath western Oregon suggests that the oceanic crust that was accreted to North America during mid-Eocene time was at least 25 km thick, thinning somewhat in northwestern Oregon and southwestern Washington. The analogous terrane in northwestern Washington and British Columbia (known locally as the Crescent terrane) appears as approximately normal thickness oceanic crust both in seismic sections and in geologic field studies, and has been thrust beneath older terranes. The apparent along-strike variation in the crustal structure of the early Eocene oceanic terrane is shown in map view in figure 4b. The western edge of the North American continent 60 mybp, as determined from geologic evidence, is also shown. Accretion of this thick terrane resulted in a dramatic westward jump of the subduction zone, greatly increasing the westward extent of the North American continent and effectively eliminating a large embayment in the western margin of North America.

Although we have yet to quantitatively explore the mechanical and geological implications of this new model of the crustal structure, a spacial correlation between the
crustal thickness of the early Eocene oceanic terrane and forearc seismicity, crustal deformation, and recent arc magmatism is clear. The lowest rate of forearc seismicity is observed where the accreted terrane is thickest. Paleomagnetic measurements indicate that this region has acted as a single block since accretion. As this terrane thins in southwestern Washington, the crust appears to have broken into several coherent blocks that have rotated relative to one another and are presently outlined by bands seismicity. The highest rate of seismicity, both in the over-riding North American and underthrust Juan de Fuca/Gorda plates, corresponds to regions where the accreted early Eocene terrane is thinnest or absent. The occurrence of post-accretion forearc volcanism and the volume of recent arc magmatism are greatest where the forearc is floored by the thinnest part of the accreted terrane.

The data on which these models are based have been published in Trehu et al., 1993a; Luetgert et al., 1993; Brocher et al., 1993; and Trehu and Nakamura, 1993. Data analysis, modeling and interpretation are discussed by Trehu et al., 1992a,b; 1993b; Trehu and Lin, submitted; Trehu et al., submitted; and Trehu, in preparation.

REPORTS RESULTING FROM THIS GRANT:


FIGURE CAPTIONS

Figure 1. Locations of the 1989 (dashed line) and 1991 (solid lines with dots signifying shot points) seismic experiments overlain on a simplified geologic map of the Pacific Northwest region. Triangles indicate volcanoes of the modern Cascade arc.

Figure 2a. Velocity model of the crust beneath the NS profile shot along the western edge of the Willamette Valley and in the Coast Range. Isovelocity contours are shown at 0.5 km/s intervals. The position of Moho for three different assumptions about the velocity in the lowermost crust is shown to illustrate some of the uncertainty in the model: A - constant 7.2 km/s lower crustal velocity; B - constant 6.5 km/s lower crustal velocity; C - 6.5 km/s south of km 150 and 7.2 km/s north of km 150. Lower crustal velocity contours are shown for model C only.

Figure 2b. EW velocity model across the Cascadia forearc beneath north-central Oregon. Velocity contours are shown at 0.5 km/s intervals.

Figure 3a. Example of the fit of the model to the data for the NS profile.

Figure 3b. Example of the fit of the model to the data from an onshore recording of offshore shots for the EW profile.

Figure 4a. Comparison of the crustal structure along the central Oregon transect to that obtained by Hyndman et al. (1989) shown at the same scale and highlighting the Siletz/Crescent terrane. The position of the base of the crust and the subducted Juan de Fuca plate east of line 2 in the Oregon transect are only shown schematically, based on fan shots and/or recent teleseismic receiver function array imaging (Nabelek et al., 1993; AGU fall meeting), and have not yet been modeled precisely.

Figure 4b. Map of the Pacific Northwest showing the approximate regional extent of anomalously thick Siletz/Crescent terrane rocks, transitional thickness, and normal oceanic crustal thickness. The inferred position of the deformation front at the present time and the inferred position at 60 mybp are also shown. The southern extent of the Siletz terrane is not well known at present, and may extend beneath the Paleozoic rocks of the Klamath terrane. Figures 3 and 4 both show a minimum lateral extent of the Siletz terrane, as the eastern boundary is poorly resolved and the western boundary may have been truncated through strike-slip motion along the Fulmar Fault.
ONSHORE
- PreTertiary
- Paleo./Eocene Volcanics
- Eocene Tyee Formation
- Marine Tertiary Sediments
- Eocene/E. Olig. Volcanics
- Olig./Miocene Volcanics
- Tertiary/Quat. Volcanics

OFFSHORE
- Plio./Pleis.
- Accret. Wedge
- L.Olig./Miocene Melange
- Paleo./Eocene Volcanics

Deformation Front
Figure 4.

(60 and 75 Ma boundaries from Dickenson, 1979; map adapted from Hughes, 1990)
Investigation

The main purpose of this project is to improve the assessment of earthquake hazard in the San Francisco Bay area. Towards this end, we are (1) carrying out a search for new earthquake data that could improve our understanding of the locations and magnitudes of historic earthquakes in the San Francisco Bay area, (2) developing magnitude-felt area relationships specifically for the Bay area, and (3) considering the relationship between stress changes and moderate-size seismicity in the region. Progress in the archival search made since our last Technical Report written in April 1993 is summarized below.

The 1992 search for new information relevant to historic earthquakes in central California yielded previously unpublished data about the 1865, 1868, 1903, and 1906 earthquakes and new information about other known as well as previously unknown 19th century earthquakes (see 1992 Project Summary and 1993 Annual Technical Report). During the 1992 investigation, we became aware of other primary sources that might contain information of potential value to this study. These sources included the minutes of verbal scientific reports and related collections of the California Academy of Sciences, 1830s correspondence and household account records of Juan Bautista Rogers Cooper archived at California Department of Parks and Recreation in Monterey, and diaries and interview materials from the 1865 to 1868 period that are currently held by the Monterey History and Art Association. With the assistance of MaryEllen Ryan (Consulting Archivist), Pennington Ahlstrand (Archivist), Barbara Keeney Clark (Archival Assistant), and Edna E. Kimbro (Historical Research Consultant), these additional primary sources have now been reviewed.

Results

In the Proceedings of the California Academy of Natural Sciences, Dr. Trask reported twenty-two earthquakes in 1865, of which the May 24 and October 8 were felt at San Francisco, Santa Clara, San Juan, and Santa Cruz. The October 8 earthquake was felt from Petaluma to Santa Cruz, and from San Francisco to Grass Valley and was followed by aftershocks through December 7, 1865. The December 7 aftershocks were reported in Watsonville. The 1868 reports were concerned with the Owens Lake earthquakes, volcanic activity of September 3 to 28, and the Hayward earthquake of October 21. Dr. Blake, George Davidson, and Dr. Gibbons presented accounts of the Hayward earthquake which, unfortunately, were not reported in the minutes.

1 Also of Geology Department, University of Maryland, College Park, MD 20742
The journals and records of Juan Bautista Rogers Cooper, half-brother of American Consul Thomas Larkin, included detailed accounts of repairs and replacement of structures at the Cooper-Molera Adobe in Monterey. Although references to the effects of the earthquakes in Santa Cruz were found, no new information about the effects in Monterey were discovered. Also in the collection, laborers account books for the years 1836 and 1838 contained no pertinent information about earthquakes. The "Memoirs of Carmel Valley" by Joseph J. Hitchcock held by the Monterey History and Art Association also were reviewed with the hope that they would provide information about the southern extent of the 1865 and 1868 earthquakes. Although the memoirs were found to be an excellent account of the genealogy, settlement, architectural history, and development of Carmel Valley, they contained no information about earthquakes.

During the 1992 search of the Santa Barbara Mission Archives, several documents were found that described earthquakes in California during the missionary period of 1769 to 1833. Of particular interest was the January 1, 1821 earthquake that caused beams to fall in Santa Inez and split a house in Santa Barbara. Following up on leads to more information about the 1821 event, a request has been made for a copy of a letter from L.A. Martinez of Mission San Luis Obispo to Colonel Don Pablo de Sola that was described in the archive index as referring to strong earthquakes at Santa Inez on January 6, 1821.

We are comparing several databases for recording information about archives, collections, and documents reviewed during this part of the project. As part of this process, we are canvassing other scientists that might utilize this database in the future about their database preferences or limitations.

Publications

This project is responsible for a number of activities associated with the Earthquake Hazards Reduction Program: Personnel maintain and operate a number of portable recording systems used in earthquake aftershock studies, install and maintain radio telemetry systems used to transmit network data to the Centers, install new seismic stations for special topical studies, maintain all the VHF, UHF, and microwave radios used in the California networks, and manage all the radio frequencies used by the Office of Earthquakes Volcanoes and Engineering.

Experiments were conducted to attempt to transmit digital data from University of California and Stanford University long period seismic stations through the U.S.G.S. operated microwave system to Berkeley. At the present time three stations are operating in this mode. Results after one year show that this method is satisfactory. All three stations are operating well with data transmission rates of about 15K baud over voice band channels.

Through verbal cooperative agreements with the U.S. Army Corps of Engineers, Sacramento District, we have been able to extend our microwave facilities along the west side of the Sierras from Oroville Dam to Lake Isabella east of Bakersfield. With this extension we are now better able to monitor the western side of the Sierras and reduce our telemetry costs. We have completed about one year of tests with several microwave channels transmitting between our Pasadena office and our Menlo Park office. Results have been excellent. This path includes U.S.G.S. and U. S. Army Corps of Engineers, Los Angeles District, links in southern California and U. S. Army Corps of Engineers, Sacramento District, and U.S.G.S. links in northern California.

This project has developed a Memorandum of Understanding with the Federal Aviation Agency Communications Section which allows us to share use of the FAA microwave system between Reno, Nevada and our microwave system at a shared facility at Black Mtn. South of Paso Robles, CA. This agreement will result in a savings of about $30,000 annually.

Personnel of this project installed 3 telemetered seismic stations near Klamath Falls, Oregon immediately following the magnitude 5.5 earthquake in late September. At present these data are transmitted both to Menlo Park, CA. and Seattle, WA.
Regional Seismotectonic Studies

9904-13010

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Investigations

1. Continued analysis of the seismicity and volcanism patterns of the Pacific Northwest in an effort to develop an improved tectonic model that will be useful in updating earthquake hazard assessments in the region. (Weaver, Yelin, co-authors from Menlo Park and Golden)

2. Continued acquisition of seismicity data across the Pacific Northwest, with emphasis on monitoring the Cascadia subduction interface, the Cascade volcanoes, and the Mount St. Helens area including the St. Helens zone. (Weaver, Yelin, Norris, UW contract)

3. Study of the Scotts Mills and Klamath Falls, Oregon earthquake sequences. (Weaver, Yelin, Meagher, Norris)

4. Study of seismically recorded rockslides and avalanches on Cascade volcanoes, with particular emphasis on a rockfall on Lassen Peak in September, 1993. (Norris)

5. Study of historical seismicity at Lassen Peak. This project is investigating earthquake swarms that occurred at Lassen Peak in 1946 and 1950. The study seeks to determine the nature of the swarms (rate of occurrence of events greater than magnitude 2.0, variation in S-P times, variations in amplitude ratios) and compare these results with similar parameters determined from better-monitored seismic swarms in the Long Valley area. (Meagher, Norris, Weaver)

Results

1. Seismic studies of the Scotts Mills, Oregon earthquake.
On 25 March 1993, at 13:34 UTC a magnitude 5.6 earthquake occurred about 5 km ESE of the small town of Scotts Mills, Oregon. The earthquake was about 55 km SSE of the center of Portland.

In the three days prior to this earthquake, three new digitally recording tri-axial force-balance accelerometers were installed within the Portland city limits. Two of these instruments triggered on the magnitude 5.6 (the third malfunctioned completely). Of the two that triggered, a recorder failure at one station prevented ultimate recovery of the data, but a calibrated, on-scale recording was obtained from the other station.
Within about 13 hours of the main shock, the first of two portable Sprengnether microearthquake recorders were deployed in the vicinity of the aftershock zone by USGS Seattle personnel. In the next four to five hours three Sprengnether DR-200 were deployed by the USGS Golden aftershock study group. In the next 42 hours nine more DR-200's were installed by the Golden group, in addition to a Kinemetrics FBA-23/Reftek sensor-recorder package near the main shock epicenter and three Kinemetric/Reftek packages in a tri-partite array on the eastern edge of the Willamette Valley, some 18 km from the center of the aftershock zone. Ten GEOS recorders and sensors were deployed by a group from the Menlo Park office of the USGS.

Figure 1 is an epicenter map showing the main shock and 115 aftershocks recorded and located by the Washington-Oregon regional seismograph network through 25 December 1993. The data from the portable instruments are being analyzed by graduate and students and faculty at the University of Washington, with some assistance from USGS scientists. Preliminary analysis suggests that the earthquake was caused by a combination of reverse and dextral strike-slip motion on a WNW striking fault. This is consistent with what it known about the regional tectonics of northwestern Oregon.

From 1969-1992 Oregon experienced very little earthquake activity, compared to Washington. The occurrence of the Scotts Mills and Klamath Falls earthquakes (see following) is a reminder that the lack of seismicity in a region over times scales of decades may not be interpreted as a lack of seismic hazard over longer time periods.

2. Study of the Klamath Falls sequence.

On 21 September 20,1993, at 03:28 UTC a magnitude 5.9 earthquake occurred approximately 21 km northwest of the town of Klamath Falls, Oregon. A magnitude 6.0 aftershock occurred at 05:45. This second earthquake occurred about 5 km northwest of the first event.

These earthquakes and their aftershocks occurred on a subsurface fault (or faults) just east of the Mountain Lakes Wilderness, along the eastern margin of Mount Harriman, Aspen Butte and Little Aspen Butte volcanic complex. The map in Figure 2 shows locations of selected earthquakes greater than magnitude 2.0. The epicenters of the two earthquakes on September 20 and the epicenter of a magnitude 5.1 aftershock on December 4 are indicated by the shaded circles. The December event is denoted by the symbol farthest to the southeast.

These two earthquakes are possibly the largest to have occurred within Oregon in this century. Only the 1936 Milton-Freewater earthquake might have been larger (its approximate magnitude was 5.8). Two persons died as a result of the earthquakes (a motorist was killed by an earthquake-triggered rock avalanche and an elderly woman suffered a heart attack). Preliminary estimates of financial loss from the earthquake are $7.6 million.

The University of Washington (UW) and the U.S. Geological Survey (USGS) in Menlo Park, CA, provided the first response by determining preliminary earthquake locations using data from their permanent seismograph networks in Washington, Oregon and northern California. USGS scientists from Seattle, Denver and Menlo Park traveled to Klamath Falls to deploy eight analog and eight digital portable seismographs in and around the aftershock zone. The first USGS instrument was installed about twenty eight hours after the first principal shock, and in the next nineteen hours seven other USGS seismographs were deployed. Over the course of the next few days the remaining eight USGS instruments were placed in the ground. The USGS portable seismographs remained in operation until October 3. By October 6 four
permanent USGS seismographs were installed in the aftershock region. These are telemetering data to the UW seismology laboratory in Seattle. These new stations allow close monitoring of the aftershock activity.

Seismologists from Oregon State University (OSU) installed the first of five portable seismographs in the aftershock zone twenty-one hours after the first shock and completed their installations in the next twenty-three hours. University of Oregon scientists installed a single seismograph twenty-one hours after the first shock. The OSU instruments were removed on October 9.

Preliminary damage estimates total about $4.23 million to publicly owned facilities, $1.14 million to residential structures, $1.96 million to commercial buildings and about $0.26 million damages to structures owned by non-profit entities. These numbers are from a report on the earthquake in the November 1993 issue of Oregon Geology (published by the Oregon Department of Geology and Mineral Industries). It was no surprise that unreinforced masonry structures were among the most heavily damaged. The large number of such structures in Oregon's building stock is a major seismic safety problem.

A. Qamar of the UW Geophysics Program and K. L. Meagher of the USGS have been combining data from the portable seismographs with data from the permanent seismograph networks in Oregon and California to more accurately locate the two principal earthquakes and their aftershocks. Their preliminary results suggest that the two principal shocks may have occurred on two separate faults (Qamar, personal communication, 1993) or on opposite sides of a bend on a single fault. Over eighteen hundred aftershocks have been recorded and located through December 10. Analysis of seismograms by seismologists at the UW and at the University of California, Berkeley indicates that both main shocks were caused by normal faulting on north-northwest striking faults (the second shock may have occurred on a more north-striking section of the fault).

Ground cracking was observed at ten sites, most of them within 6 miles of the main shock epicenters (see November 1993 issue of Oregon Geology). These features are explainable by settling and spreading in mostly artificial fill. No convincing evidence was found for actual fault rupture extending to the surface. This is not unusual for a magnitude 6 earthquake.

Geologists have mapped several faults north, south and west of Klamath Falls that have had probable seismic displacement upon them within the past 10,000 years. The Klamath Falls area is on the boundary between two major geologic provinces: the Cascade volcanic province to the west and the Basin and Range province to the east. This boundary is the site of ongoing tectonic activity as witnessed to by these earthquakes and the presence of many young faults. Consequently, we can expect that earthquakes as large as or larger than the earthquakes of September 1993 will occur in the future in the Klamath Falls area, though unfortunately we cannot say when they will occur.

Reports


Figure 1: Seismicity near Scotts Mills, Oregon. Small triangles are seismic stations deployed after the mainshock, open circles are the aftershocks. Mainshock location is shown by filled circle.
Figure 2: Seismicity near Klamath Falls, Oregon. See text for explanation.
Regional Setting of the Parkfield Earthquake

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INVESTIGATIONS

Regional maps have been compiled in digital form showing topography, geology, gravity, aeromagnetics, and seismicity of the Parkfield region (see Index Map below). This work, done in cooperation with R.C. Jachens, R.W. Simpson, and A.J. Michael, has produced a digital database in the commercial Geographic Information system ARC/INFO that can be used both to prepare various cartographic images (maps) and for spatial and topical analysis. Information can be extracted from the database in ARC/INFO according to spatial and topical criteria and used to prepare plots or serve as input data for manipulation and analysis, or can be converted to other file formats for use in other programs.

Index map of Parkfield study area.

RESULTS

Plotting and comparison of the datasets using common scales and projections proves to be a powerful analytic procedure in itself, and can be combined with more specific analysis including the digital construction of cross sections from the database. Subhorizontal structures interrupt the vertical continuity of the highly deformed rocks east of the San Andreas fault near Parkfield but are not obvious in the surface geology. The Coalinga-Kettleman anticlines along the west edge of the San Joaquin Valley reflect underlying blind thrusts that extend westward at depths of 10-15 km probably to or even beneath the San Andreas fault. Earthquakes are largely confined to the eastern parts of these thrusts and to the vertical San Andreas fault, where the absence of hypocenters below 17 km permits truncation of the San Andreas by the thrusts. Five km of structural relief on the exposed White Creek syncline west of Coalinga do not influence an upper crustal discontinuity defined by a thin sheet modeled as magnetic serpentinite that extends in the shallow subsurface (2-5 km) from New Idria south to Table Mountain. Franciscan rock exposed near Middle Mountain coincides with a gravity low, implying thrusting over lower density rocks; Franciscan rock southeast of Gold Hill is not dense enough to account for high gravity values (10 mGal excess). In contrast to these subhorizontal structures, large, deeply-penetrating (>10 km) bodies modeled as magnetic serpentinite occur at New Idria (top exposed) and at the southern end of the Parkfield fault segment. (Wentworth, Jachens, Simpson, and Michael, AGU abs, 1992)

REPORTS


Pinon Flat Observatory:  
A Facility for Studies of Crustal Deformation

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Program Elements II.3 and II.7

This grant supports the operation of Piñon Flat Observatory (PFO) as a research center for the study of crustal deformation. Through this grant, the U.S. Geological Survey provides half of the funding needed to run the 160-acre facility and to maintain the reference-standard instruments there. Matching funds are provided by a grant from the National Science Foundation. The work done at PFO includes establishing the most reliable record of crustal deformation possible, something attained by operating the best instruments available and by a systematic intercomparison of results from many types of sensors. The result is an accurate record of strain and tilt changes in the area near the observatory, between the active San Jacinto fault and southern San Andreas fault systems; and from this, a better understanding of the mechanics of faulting.

The site continues to be utilized by roughly 20 different research teams. Figure 1 shows the results of some of their work, namely the record of strain change in the NW-SE direction gotten by three types of measurement over the last 6 years. Two are geodetic measurements, made in the area around PFO by USGS investigators: Geodolite data (collected from 1974 to 1991, though now ended), and two-color EDM data (collected from 1986 to the present, and continuing). The third is the continuous record made by the NW/SE laser strainmeter.

From the standpoint of instrument comparison, two points are evident from this figure:

1. The long-term strain rates found by the two sorts of geodetic systems are in fair accord, both being $3 \times 10^{-8}$ yr$^{-1}$. This rate, though low (as would be expected for a measurement roughly parallel with the local strike-slip faults) is significantly different from zero, indicating that there is more to the strain field than simple shear. The laser strainmeter appears to be showing a rate in excellent accord with the long-term geodetic rate. So far as we know, this is the only example of geodetic and continuous data agreeing on a secular rate, and the signal here is a relatively small one.

2. At any period shorter than the secular rate of change, the strainmeter provides a much better measure of strain changes than the geodetic measurements do—and it should be noted that these geodetic measurements, over these distances, have a precision that equals or exceeds GPS. At periods of a few days this advantage is a factor of $10^3$ or more, even if the geodetic measurements were made daily.

Of course, having established that the strainmeter gives a more reliable record of short-term strain changes, we need to ask what these changes tell us about the earth. Here two points are evident:
1. By and large, the strain does not show any large changes; except at the times of earthquakes (and not always then), the fluctuations over a year's time are less than the daily tidal cycle. We would expect the same to be true of the stress. Since it is pretty well established that tides do not cause clear earthquake triggering, it seems unlikely, barring some kind of rate-dependent weakening, that the changes in seismicity sometimes seen over time scales of a few months can be caused by underlying strain changes.

2. However, there are clear changes of strain associated with some earthquakes: in this record, the North Palm Springs earthquake (unfortunately confused by a drilling exercise soon after) and, very clearly, the Landers earthquake. (For both of these the coseismic offset has been omitted). Note, however, that the Joshua Tree event, three months before the Landers event, did not cause any strain-rate change. The Landers shock created the most rapid and distinctive postseismic strain change we have ever seen, though, as this figure shows, it was a transient one, it still represents a larger strain change in a month than we normally see in several years. While the cause of this signal (whether postseismic fault slip or crustal relaxation) is still unclear, its mere existence suggests that we have observed a phenomenon that must be taken into account in any model for the interaction of earthquakes.

Postseismic motions from the Landers earthquake were also observed by a group at UCLA using GPS data collected near the Landers rupture, though with much poorer signal-to-noise than the strainmeter. Figure 2 shows these results for a representative line, along with an expanded version of the NW/SE strain shown in Figure 1. The GPS data alone cannot show the early stages of the postseismic response, and so suggest a somewhat slower time constant than fits the strainmeter data. The remarkably smooth nature of the transient is likewise also evident only in the strain data, and must be explained by any model of it.

To be able to improve on the GPS measurements shown in Figure 2, we need to continue to improve the performance of GPS systems, which will mean understanding the errors in them. As a step toward this, as well as a necessary element in the operation of the permanent GPS stations at PFO, we have been investigating the "ties" made between stations at the observatory. While these only cover short distances, this allows us to draw some conclusions about the performance to be expected for an actual field measurement (under ideal conditions).

There are a number of points at PFO at which we have made repeat GPS measurements; by far the most frequently occupied are:
- PIN1, the permanent tracker of the PGGA (run by Dr. Bock of UCSD). The antenna for this mounts on a fixed tripod, though with a fixture that allows for different types of antennas; and over the life of this installation several different types have been used. The bulk of the PGGA measurements have been made with a Rogue system (Dorn-Margolin antenna with choke ring), though when the Rogue has been unavailable Ashtech equipment has been used instead. Trimble equipment has been used for some of the ties to other locations.
- PIN2, the other permanent site, is also a fixed tripod, with the antenna mounting on a standard survey thread, so that the height, but not the horizontal location, can vary in practice. This installation has been used for a local-scale (14 km) continuous GPS measurement, and has always been occupied by the same, Trimble, antenna.
- PINY is a standard survey disk (PINYON FLAT 1981 NCMN) mounted in a large concrete pad, and used as the reference point for VLBI measurements from 1983 through 1990. When used for GPS measurements, it has always been occupied by Trimble equipment.
Figure 3, and the table below, summarize our results; we have ended up using a wide range of software packages, also a useful test (the GIPSY results are from preliminary analyses by Dr. Kristine Larson).

<table>
<thead>
<tr>
<th>Date(s)</th>
<th>Antenna at PIN1</th>
<th>Software</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1990:062-064</td>
<td>Trimble</td>
<td>TRM640</td>
<td>Initial survey tie between marks; PIN1-PIN2 results from differencing PINY-PIN2 and PINY-PIN1.</td>
</tr>
<tr>
<td>B 1990:156</td>
<td>N/A</td>
<td>TRMMBP</td>
<td>Part of a survey of the Pinyon Flat 2-color EDM net</td>
</tr>
<tr>
<td>C 1992:077</td>
<td>N/A</td>
<td>GAMIT</td>
<td>Average of 6 days of results</td>
</tr>
<tr>
<td>D 1992:199-205</td>
<td>Rogue</td>
<td>GAMIT</td>
<td>Average of all results from routine reduction of this line as part of 14-km GPS experiment</td>
</tr>
<tr>
<td>E 1991</td>
<td>Rogue/Ashtech</td>
<td>GAMIT</td>
<td>Byproduct of NASA footprint survey around PINY; fixed (low) setup at that point; 6-hour sessions.</td>
</tr>
<tr>
<td>F 1992:144-153</td>
<td>Rogue</td>
<td>GIPSY</td>
<td></td>
</tr>
<tr>
<td>G 1992:230</td>
<td>Trimble</td>
<td>GAMIT</td>
<td></td>
</tr>
<tr>
<td>H 1992:230</td>
<td>Trimble</td>
<td>GIPSY</td>
<td></td>
</tr>
</tbody>
</table>

While we are still working on understanding these results, several points are clear:

1. We found many instances where field notes were not properly carried forward into the processing. Only by virtue of knowing the truth were these found and their effects removed.

2. The differences between sophisticated software packages, over these distances, are less than 1 mm—though we need to understand the reasons for the differences.

3. There is no conclusive evidence for bias associated with mixing antennas (this is expected to be more severe in the vertical).

4. The consistency of the results for surveys (F) and (H) suggest negligible monument motion associated with the Landers earthquake.

5. To get reliable ties at the 5 mm level should not be difficult; to get them at the 1 mm level will be.
Longbase and Geodetic Strain – NW–SE

Corrected Strain (w & wo tides)

Geodetic Strain

Open – One-Color EDM Net
Solid – Two-Color EDM Net
Dash – Longterm geodetic average

Daily Precipitation
2.5 cm/div

1 - freq unstable
2 - drilling
3 - vault temp

Eight Years

Figure 1.

Strain, Near-Field GPS, and Models -- Postseismic Comparison

Offsets removed and Detided

UCLA-Model Predicted Strain

Joshua Tree

Landers

5-day Exponential

Boxes – Representative Near-field GPS
(scaled to equivalent far-field strain)

1 - Thermostat stuck

Figure 2.
Figure 3.
Deformation Monitoring of the Southernmost San Andreas Fault

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Program Element II.3

This grant supports the operation of an optical-fiber monument anchor test site, and construction of a long-base laser strainmeter, both installed at the southernmost end of the San Andreas fault in the Coachella Valley. The initial optical fiber experiment had been designed to establish if good anchoring was possible in the clayey material of the Coachella Valley; construction of the strainmeter was proposed following the demonstration that this was indeed so. Installation of a long-base strainmeter should be highly enlightening in trying to understand the style of crustal deformation in this tectonically active area—an area posited as a likely epicentral region for a M 8 earthquake.

The optical fiber experiment involves measuring the differential vertical motion of four points in the ground from depths of 1.65 to 48 m, to determine the appropriate depth (if any) for anchoring long-base instruments. Figure 1 shows recent results of these measurements. We have found that the ground above 8 m can be quite unstable, showing motions as much as 0.5 cm in response to local surface wetting. (The largest effects evident in the plot are due to nearby surface-irrigation, but other displacements are evident at times of heavy rains.) In contrast the deformations over the deepest interval monitored, 23 to 48 m (a span eight times greater than above), have proven this ground to be quite stable, with little more than an apparently steadily accumulating extension amounting to 0.4 mm/yr. This and other measurements suggest that ~20 m is deep enough for stable anchoring. We continue to run this experiment as it continues to provide insights into the behavior of the valley materials and because operating it, in conjunction with the many construction trips to the area, demands little effort on our part.

Our design for the long-base instrument at Durmid Hill (hereafter DHL) was based on two goals:

1. To achieve the best possible record of continuous deformation at the terminus of the San Andreas fault, by constructing a long-base laser strainmeter that is as low-maintenance as possible.

2. To make the instrument as “portable” as possible. Though this may seem an odd notion for something so substantial, we sought in our design to make sure that everything not sunk in the ground could be removed and re-installed elsewhere. This aspect of the design is in keeping with our expectation that the installation at Durmid Hill is not to turn into a permanent one.

Construction at the site (part of the California State Park system) began in March 1992, and involved a major effort throughout the spring of that year which resulted in opening the site to construction equipment (roads and bridges), drilling of the anchoring boreholes, excavating of vault pits(3), trenching, and precise installation and burial of 525 m of PVC vacuum-pipe casing. By June of 1992 virtually all the skilled surveying and construction work was completed. Work was then brought to a standstill by the combination of responding to the Landers earthquake, by the loss both of our long-time caretaker at PFO, and by the ill-health of our chief engineer, which eventually forced him to go on disability. (Unfortunately, until this was settled, which took a year and a half, we were not allowed to hire a replacement).
Because of these difficulties (most especially the lack of personnel) we were forced to change our plans for completing the installation by late 1992. Only in the fall of 1992 did we begin the detailed design of the laser strainmeter components—some 65 pages of drawings—basing them on the plans for the two-decade earlier laser strainmeters built at Piñon Flat Observatory. The bulk of this was carried out by a skilled temporary engineer, requiring about a month’s effort. Starting in 1993 we were able to combine the efforts of an entry-level part-time (occasional) engineer and an undergraduate student (even more occasional) to carry out the substantial amount of field assembly work needed to complete the instrument: distribution of power to the site; vault construction and installation (3); electrical and signal wiring; and preparation and installation of 525 m of vacuum-pipe tubing for the strainmeter itself. All of this has been done well, and done below budget, though at the expense of time.

Figure 2 (an assembly drawing produced from the shop drawings) shows a sectional view of one end of the laser strainmeter. This instrument is identical in principle to the existing laser strainmeters at PFO: a Michelson interferometer with one of its optical arms spanning an extended path, which needs be evacuated to remove the effects of variations in the index of refraction of air. However, many of the details reflect improvements suggested by our long experience at PFO. One of the reasons the field-construction work has taken so long is that the entire installation is buried, and this proved much more difficult than we imagined; the clayey material there and the extreme weather conditions have caused us considerable grief. At this stage we believe that (for this location at least) the effort to bury everything will prove worthwhile because of the isolation from the thermal extremes and the physical isolation of the end-piers from the surface layers which, among other things, completely lose their character and turn into impassible “gumbo” when wetted. All-in-all burial of the instrument should provide for a much better measure of strain. As the figure shows, the vaults were built from used shipping containers; at each end concrete pads were poured to support optical tables on which two interferometers will soon be installed. One will be for the primary sensor, the horizontal strainmeter, while the other will monitor the lengths of two optical fibers extending downward in inclined boreholes to a depth of 25.6 m. These sensing fibers will serve to “anchor” the strainmeter to more stable points at depth.

As is clear from Figure 2, the complete installation is not a small job; at the time of writing all the equipment has been fabricated, the vaults and vacuum pipe have been installed, all utilities connected, and all auxiliary equipment installed; we expect to have the vacuum system switched on, the optical parts in, and the instrument in operation, by February 1994.
Figure 1.
Investigations

Cheryl Hummon and Craig Schneider are completing structure contour maps of the top Repetto, top Delmontian, top Mohnian, and the Nodular Shale for the region between East Beverly Hills oil field and Las Cienegas oil field. In addition, Craig completed a 2D and 3D dislocation modeling study, working with Ross Stein at USGS. Hiroyuki Tsutsumi is working west of East Beverly Hills across the extension of the Newport-Inglewood fault to Santa Monica. Gary Huftile has re-drawn balanced cross sections of the Ventura region to consider the downward extension of major reverse faults as ductile shear zones in the lower crust.

Results

Wilshire arch and blind thrust:

The blind thrust forming the Wilshire arch was modeled as a fault-bend fold and by 2D and 3D dislocation modeling. The fault-bend fold model predicts a dip slip of 1.5 km based on the length of the back limb. A 2D dislocation model of a fault embedded in an elastic half-space gives comparable values for dip slip, but it does not duplicate the Wilshire arch as defined by structure contours of the base of Quaternary marine gravels. The best fit is with a 3D model with 1.0 m of dip slip and 1.1 m of strike slip on an oblique-slip, right lateral-reverse fault with 1.5 m of net slip. This model shows the Hollywood basin and Wilshire arch in their correct configuration (Figure 1). The 400-m amplitude of the Wilshire arch could be produced by 1700 slip increments described above in the last 0.8-1.0 m.y., a slip rate of 2.6-3.2 mm/yr based on a total slip of 2.6 km. The high slip rate suggests that the Wilshire blind thrust is taking up more than 25% of the shortening across the LA basin as measured by GPS. The Wilshire blind thrust mapped with both the fault-bend fold model and the 3D dislocation model is located in the vicinity of a north-dipping zone of microearthquakes (Figure 2). Focal-mechanism solutions of these earthquakes, however, are inconclusive. A paper describing the Wilshire arch and blind thrust has been submitted to Geology.

The right-slip component suggests that right slip on the Whittier fault may be transferred west to the fold-thrust belt. Right slip on the fold-thrust belt should be considered in balanced-cross-section models that account for only dip slip, because strike slip requires that material is moving into and out of the section, posing constraints on cross-section balancing.
Structure west of Newport-Inglewood fault zone:

The fold-thrust belt west of the Newport-Inglewood fault differs greatly from the belt east of the fault. The Sawtelle oil field is cut by a large subsurface thrust (Santa Monica fault) with >2 km reverse separation of lower Mohnian Nodular Shale. To the east, this thrust branches into at least 4 subsurface thrusts in the Beverly Hills and Cheviot Hills oil fields. The south-facing topographic scarp mapped by J. Dolan and K. Sieh as the active trace of the Santa Monica fault is north of the subsurface Santa Monica thrust and north of all four thrusts at Cheviot Hills and Beverly Hills.

Active thrusts reactivate Miocene normal faults:

In the Sawtelle oil field, middle to late Miocene strata are thicker on the hanging-wall side of the north-dipping Santa Monica thrust, whereas Delmontian and Repettian strata are thicker on the footwall side. This indicates a change in slip direction from normal to reverse. Similarly, north of the Las Cienegas oil field, the north-dipping San Vicente reverse fault marks a boundary between thick middle Miocene Topanga Formation in the hanging wall to the north and thin Topanga to the south. Also, the lower half of the Miocene Puente Formation is thicker on the north side of the fault, indicating a continuation of the same stress field in underlying basement. Slip direction changes to north-side-up in the upper part of the Puente Formation at about the same time as the change occurred at the Sawtelle oil field. This indicates that at least some of the thrusts follow pre-existing Miocene normal faults formed under a stress regime very different from today. Fault orientation, therefore, must be used with considerable caution in reconstructing present-day stress fields. Pre-existing zones of weakness may be reoccupied by younger faults even though these zones may not be favorably oriented in the plane of maximum shear stress.

LA Metro Rail samples:

These samples from the Wilshire arch contain a Middle/Lower Pico benthic foram assemblage, suggesting an age of 1.5-2.5 Ma according to Blake (1991). However, volcanic ash from these samples studied by Andrei Sarna-Wojcicki and diatoms studied by John Barron indicate an age of ~5.4-6 Ma (Ponti et al., 1993). This may require a revision of slip rates on blind thrusts based on benthic foram stages.

Convergence rates across the coastal Ventura basin:

4.6 years of GPS surveying (Donnellan et al., 1993, Nature 366:333-336) give shortening rates of 7-10 mm/yr, less than half the geological rates. We had assumed an age of the top of the Saugus Formation as 200 ka based on amino-acid racemization estimates, but we revise this to 500 ka based on a new paleomagnetic section near Magic Mountain in east Ventura basin (Levi and Yeats, 1993). Our shortening rates assumed that basin-bounding Oak Ridge, Red Mountain, and San Cayetano faults merged into décollements at the brittle-plastic transition. If the faults continue downward as ductile shear zones, the convergence rate contributed by a given fault is the near-surface slip rate times
the cosine of the fault dip angle. Using these two changes in our assumptions, 
the geologic slip rates are in agreement with the geodetic slip rates (Yeats, 
1993).

Reports

Hummon, C., Schneider, C.L., Yeats, R.S., Dolan, J.F., Sieh, K.E., Huftile, G.J., 

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Schneider, C.L., Hummon, C., Yeats, R.S., and Huftile, G., 1993, Locating the 
Geophys. Union 74/43 supplement:434

Figure 1a. Structure-contour map of the base of Quaternary marine gravels; contour interval 50 m. Shaded patches are topographic scarps mapped by J. Dolan and K. Sieh. Abbreviations: WBHL, West Beverly Hills lineament; NIF, Newport-Inglewood fault. b. 3D elastic dislocation model of a fault with right-reverse slip of 1.5 m. Contour interval 50 mm; supplemental dashed contours at 20 mm. Total fold amplitude 230 mm. After Hummon et al. (submitted).
Figure 2. Cross section along line A-A' of Figure 1 showing possible locations of the Wilshire blind thrust. Abbreviations: Qmg, Quaternary marine gravels (diagonal-lined pattern); Qal, Quaternary alluvium. Shaded area represents approximate location of a zone of micro-earthquakes; location errors ±1 km horizontal and ±2 km vertical. After Hummon et al. (submitted).
Global Seismograph Network Evaluation and Development

9920-68152

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Investigations

Continued work in support of the US/USSR Joint Seismic Program.

Results

Equipment was ordered, assembled, and tested for new Global Seismograph Network (GSN) stations at Yakutsk, Republic of Sakha, Yakutia, Russia; Petropavlovsk, Kamchatski, Russia; and Magadan, Russia. Ten engineers from the stations were trained over a two-week period at the Albuquerque Seismological Laboratory. Construction of vaults was initiated at Magadan and Petropavlovsk so that completion would coincide with the shipment of equipment and arrival of installation team. The equipment and installation team were flown to Magadan in August on a chartered Aeroflot plane. The equipment necessary for two seismic stations was transferred to another Aeroflot aircraft. Two teams along with the equipment were then dispatched to Petropavlovsk and Yakutsk, and the third team began pre-installation actions at Magadan. As the installations proceeded at Yakutsk and Petropavlovsk, individual team members returned to Magadan to complete the Magadan installation. Yakutsk was operational on September 8th, Petropavlovsk on September 15th, and Magadan on September 23rd. The Yuzhno-Sakhalinsk seismic station was resupplied with the required operational, as well as administrative supplies. Software was upgraded and the data processor was modified at Yuzhno-Sakhalinsk. Site surveys for future seismic sites were not possible due to fuel shortages in Russia, unreliable flight schedules and the volatile political situation. The Garni, Armenia, seismic system was flown to the Albuquerque Seismological Laboratory (ASL) for upgrade. The system was upgraded, returned to Garni and is now operational. Conducted training for the Global Telemetered Seismograph Network and China Digital Seismograph Network personnel at ASL.
Through a cooperative project between Stanford University and the National Geodetic Survey (that was sponsored by the NEHRP program), NGS conducted a re-survey of triangulation stations in the Caruthersville network (Fig. 1) with the global positioning system (GPS) in 1991. This work revealed that substantial strain accumulation occurred over a ~40 year epoch consistent with the accumulation of right-lateral shear strain due to ductile slip at depth along the strike slip fault zone extending from Marked Tree AK to Caruthersville, MO (Liu, Zoback and Segall, Science, v. 257, 1666-1669, 1992). In this project we have continued our study of interseismic strain accumulation in the New Madrid seismic zone and we conducted a new survey of the Caruthersville network in July, 1993. We used Trimble 4000 SST dual-frequency GPS receivers co-owned by Stanford University and UNAVCO. The purposes of the new survey were:

1. to reoccupy the Caruthersville network and re-check the shear strain results from triangulation -1991 GPS study;

2. to expand coverage to the south and getting more stations in the direct vicinity of the seismicity;

3. to expand coverage to the east to straddle the southeast rift zone boundary;
(4) to tie the Caruthersville network to the regional network run by Northwest University through stations Bluffport, Williamson, and GPS47.

(5) to obtain GPS-GPS geodetic measurements to attempt to detect measurable strain during the 2 1/2 year epoch between surveys.

Thirty-six stations were occupied by 6-hour sessions separated approximately one week. During the first occupation, we used MID3 as the base station, and used HAYT for the second occupation. We did two sessions per day, one from 6:00 AM to 12:00 AM, the other was from 8:00 PM to 2:00 PM local time. During most of the survey, there were more than 6 GPS satellites could be tracked. We arranged the schedule such that every station was occupied once during the day time and once at night to improve the quality of the data. Most of the stations used in 1991 were in good condition, but two stations had been destroyed necessitating the use of remote marks. The data are currently being processed utilizing the GIPSY software package developed at the Jet Propulsion Lab.
INVESTIGATIONS:

1. Modeling of local stress anomalies related to dense lower crustal rift pillows that may be responsible for localizing intraplate seismicity.

2. Investigation of the Quaternary stress state and style of deformation in Walker Lane belt of the Basin and Range province.


4. Maintaining and updating a global compilation of contemporary in-situ stress data compiled as part of the World Stress Map Project, an international collaborative effort including over 40 scientists from over 30 different countries and lead by the project chief.

RESULTS:

1. The state of stress in the vicinity of old continental rifts is examined to investigate the possibility that crustal structure associated with ancient rifts (specifically a dense rift pillow in the lower crust) may actually modify the regional stress field and increase the likelihood of brittle failure. Both shallow (2.0-2.6 km depth) breakout data and deep (20-45 km depth) crustal earthquake focal mechanisms indicate a consistent N to NNE maximum horizontal compression in the vicinity of the Amazonas rift in central Brazil. This stress direction is nearly perpendicular to the rift structure and represents a roughly a 90° stress rotation relative to the regional E-W compressive stress field within the South American plate. Simple elastic 2-D finite elements of the density structure associated with the Amazonas rift (as inferred from independent gravity modeling) indicate that elastic support of this dense feature generates rift-normal compressional stresses between 60-200 MPa, with values of 80-100 MPa probably most representative of the overall structure. The observed ~90°stress rotation indicates that the rift normal stress must be greater than the regional horizontal stress differences. Thus, the inferred regional horizontal stress differences are <80-100 MPa, significantly less than predicted maximum shear stresses (maximum horizontal stress-vertical stress) of about 800 MPa for mid crustal depths (~20 km depth) determined from lithospheric strength envelopes based on the frictional strength of the...
most well-oriented faults. This difference may be explained by a relatively small difference in relative horizontal stress magnitudes possibly related to pore pressure effects at depth. The calculations and the observed rotation demonstrate that rift-normal compressive stresses are a significant source of stress acting on the lithosphere and may be a major contributing factor to the association of intraplate seismicity with old zones of continental extension.

2. The NW- to N-trending Walker Lane Zone (WLZ) is located along the western boundary of the northern Basin and Range province and the Sierra Nevada. This zone is distinguished from the surrounding Basin and Range province on the basis of irregular topography and evidence for both strike-slip and normal Holocene faulting events. Inversion of slip-vectors on active faults, historic fault offsets, and earthquake focal mechanisms indicate two distinct Quaternary stress regimes within the WLZ, both of which are characterized by a consistent WNW $\sigma_3$ axis: a normal faulting regime with a mean $\sigma_3$ axis of $N95^\circ \pm 9^\circ$ E and a mean $R$ value ($R=(\sigma_2-\sigma_1)/(\sigma_3-\sigma_1)$) of 0.63-0.74, and a younger strike-slip faulting regime with a mean $\sigma_3$ axis of about N110$^\circ$ to 115$^\circ$ E and significant $R$ values ranging between about 0.1 and 0.2 which is compatible with historic fault offsets and earthquake focal mechanisms. ($R=0$ in either regime indicates a stress regime transitional between strike-slip and normal faulting.). Both the Quaternary extensional and strike-slip stress regimes reactivated inherited Mesozoic and Cenozoic structures and also produced new faults. The present-day strike-slip stress regime has produced strike-slip, normal oblique-slip and normal dip-slip historic faulting.

Previous workers have explained the complex interaction of active strike-slip, oblique, and normal faulting in the WLZ as a simple consequence of a single stress state with a consistent WNW $\sigma_3$ axis and transitional between strike-slip and normal faulting (maximum horizontal stress $\parallel$ vertical stress, or $R \sim 0$ in both regimes) with minor local fluctuations. Our slip data, including cross-cutting striata on the same fault plane, support previous results from Owens Valley [Zoback, 1989, *JGR*, v. 94, p. 7105-7128] that indicate deformation within temporally distinct normal and strike-slip faulting stress regimes with a roughly constant WNW-trending $\sigma_3$ axis. A recent change from a normal faulting to a strike-slip faulting stress regime is indicated by the cross-cutting striata on faults in rocks <300,000 yrs old, and is consistent with the dominantly strike-slip earthquake focal mechanisms and the youngest striata observed on faults in Pli-Quaternary deposits. Geologic control on the timing of the change is too poor to determine if there has been a single recent absolute change or if there is an alternating or cyclic variation in stress magnitudes. Thus, this current investigation allows to indicate that the deformation in the WLZ (including along the Owens Valley) could not be explained by strain partitioning as suggested by Wesnousky and Jones [1992, *EOS*, v. 73, p. 560]. The normal dip-slip movement on the Nevada frontal fault west of the Owens Valley is related to a normal faulting stress regime, while the strike-slip faulting within the Owens Valley is due to a recent strike-slip faulting stress regime. Thus, these two different slip-faulting are not the consequence of "strain partitioning" within a single regional stress field. The location of the WLZ between the deep-seated regional extension of the Basin and Range and the right-lateral strike-slip regional tectonics of the San Andreas fault zone is probably responsible for the present-day complex interaction of tectonic regimes in this transition zone. In early to mid-Tertiary time the WLZ appears to have had a similar deformatonal history, in this case as a back-arc or intra-arc region, accomodating at least part of the right-lateral component of oblique convergence.

3. The northern Nevada rift extends for at least 500 km with a continuous NNW trend from southern Nevada to the Oregon-Nevada border. The regional extent of the rift is defined principally on the basis of aeromagnetic data, but the magnetic anomaly is clearly related in various places along the rift to exposures of basaltic dikes and flows erupted between 14 and 17 Ma. The rift is particularly well exposed in the Roberts Mountains, where a dike swarm extends 10 km with a consistent N22$^\circ$W trend. Individual dikes in the Cortez Range are
continuous in outcrop and have similar NNW trends over distances exceeding 5 km. The northern Nevada rift is equivalent in age, trend, and chemistry to feeder dikes of the Columbia Plateau flood basalts in northeastern Oregon, and both regions are considered to be part of an enormous lithospheric rift that rapidly propagated NNW and SSE, respectively, from a central mantle plume. The plume was probably centered at the McDermitt volcanic center near the Oregon-Nevada border and represents the initial breaching of North America by the Yellowstone hotspot. The present NNW trend of the rift reflects the state of stress in the Basin and Range during middle Miocene time, assuming that the rift has not rotated since its emplacement. Recent paleomagnetic evidence presented by others and based on three localities along the rift suggests that parts of the rift may have rotated approximately 19° counterclockwise, thereby casting doubt on its suitability as an indicator of middle Miocene stress. However, predicted offsets of the rift based on block-rotation models are in the opposite sense of observed offsets. Moreover, the orientations of feeder dikes within the rift are statistically equivalent to the overall orientation of the rift, and this relationship could only be preserved during rotation if the 500-km-long rift rotated as a single unit, a model which is inconsistent with surrounding Basin and Range deformation.

4. For the past 6 years the project chief, Mary Lou Zoback, has headed an international project to compile and interpret intraplate tectonic stress data, the World Stress Map Project, as part of the International Lithosphere Program. This collaborative effort involves over 40+ scientists in over 30 countries, and has resulted in over 6500 reliable determinations of tectonic stress orientations and relative stress magnitudes globally. Publication of a special issue of JGR on the World Stress Map project in July, 1992 (including a large size color plate of maximum horizontal stress orientations on a base of average global topography) and the accompanying release of the entire dataset through the NGDC (National Geophysical Data Center, NOAA) marked the completion of this project. The global stress compilation will continue under a new International Lithosphere Program project on the state of stress in sedimentary basins headed by Sebastian Bell of the Canadian Geological Survey (see Zoback and Burke, 1993, reference given below for details).

REPORTS

papers:


SEISMOTECTONICS OF THE SAN FRANCISCO PENINSULA

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INVESTIGATIONS:

1. Investigation of seismicity on the San Francisco Peninsula and along the extension of the San Andreas fault offshore from the Golden Gate bridge. Special emphasis was placed on the 1957 (M=5.3) and the 1958 (M=4.7) earthquakes near Daly City which are the largest post 1906 earthquakes along the San Andreas north of the Loma Prieta rupture. These events are being studied in relation to on-going deformation of the region indicated by post-1969 microseismic deformation.

2. Careful analysis of the sparse seismicity located beneath the San Francisco Bay and along its margin. Detailed evaluation of these events was necessary to interpret the real, well-located seismicity in order to attempt to relate this seismicity to recently identified active deformation in this area.

RESULTS:

1. Well-located earthquakes along the San Francisco peninsula indicate two main loci of seismic activity: a 45 km-long zone that runs between Lower Crystal Springs Reservoir and Bolinas Bay, (including the offshore region west of the Golden Gate) and a 35 km-long zone that extends between the towns of Los Gatos and Woodside, immediately north of the Loma Prieta rupture (Figure 1). These two loci of activity are separated by a roughly 20 km-long zone of seismic quiescence. Most epicenters in the Golden Gate zone are concentrated within about 2 km of the mapped trace of the San Andreas fault, forming potentially the longest, persistently active stretch of the 1906 rupture. This zone includes a ML=5.3 earthquake in 1957 as well as the probable nucleation site of the 1906 San Francisco earthquake itself (Bolt, BSSA, 1968; Boore, BSSA, 1977). In contrast, seismicity in the Woodside-to-Los Gatos zone is much more diffuse, and located within a 10 km-wide band of mapped Quaternary thrust or reverse faults and folds on either side of the San Andreas fault.

The best-constrained focal mechanisms for all M>2.5 events on the peninsula between 1984 and 1992 also indicate a marked contrast in deformation style between these two seismically active zones. Mechanisms in the Woodside-to-Los Gatos zone show dominantly thrust/reverse faulting with the maximum horizontal stress oriented nearly orthogonal to the San Andreas fault, a pattern

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Figure 1. Map of relocated seismicity (1969-1993) in the San Francisco Peninsula study region (area outlined by shaded lines). Location criteria: rms < 0.25 s; recorded at more than 5 stations; horizontal error < 2.0 km; vertical error < 4.0 km. Events scaled proportional to magnitude, with largest magnitude M=5.2 (Loma Prieta aftershock) occurring at the southeastern end of the study area. SFO=San Francisco airport, OP=Oyster Point, DC=Daly City, HPFZ=Hunters Point fault zone, CPFZ=Coyote Point fault zone.
observed regionally within the California Coast Ranges including along the East Bay fault system. In contrast, mechanisms in the Golden Gate zone indicate dominantly strike-slip and normal faulting, the latter with NE-to-E-trending T-axes, implying roughly fault normal extension. These normal faulting mechanisms occur offshore and correspond to a ~2 km right offset in the onshore mapped traces of the San Andreas fault north and south of the Golden Gate.

The extensional deformation in the Golden Gate zone is in marked contrast to longer term geologic evidence of compressional tectonism on the northern San Francisco peninsula (which comprises the southern part of this 40 km long seismicity zone). Here, Quaternary thrusts are subparallel to the San Andreas fault and bound moderate to steeply tilting blocks of Merced formation (~3.0-0.5 Ma). Further complexity is indicated by the focal mechanism of the largest post-1906 earthquake in this region, a m=5.3 event on 22 March 1957. Rechecking of original first motion picks (Tocher, 1959, CDMG Report 57) and waveform modeling confirm that the 1957 event was not compatible with right lateral strike-slip faulting on a NW-trending plane but rather indicates dip-slip movement on either a low-angle decollement plane, or alternately, on a steeply dipping (75°-90°) fault plane, both subparallel to the San Andreas fault. On-going analysis of microseismicity is required to better define seismic hazard in this important metropolitan region, including that due to future strike-slip events as well as possible hazard related to unidentified blind thrusts, decollements or offshore normal faults. An opportunity also exists to investigate significant parameters (such as potentially temporally varying fault normal extension) that might control nucleation of a major earthquake on the San Andreas fault.

2. A careful analysis of the sparse seismicity beneath the San Francisco Bay and its margin for the time period January 1969 and November 1993 was carried out to: (1) assess the location errors associated with the hypocenters, (2) discriminate earthquakes from quarry blasts, and (3) to analyze and interpret the seismicity according to its association with active deformation in the area.

Most of the seismicity is diffuse, with the notable exception of two clusters of hypocenters near San Francisco airport (SFO) and east of Oyster Point (OP) (Figure 1). In the time period of recording, the maximum magnitude of events beneath the Bay and its margins is M=2.9; 41 events have had M≥2.0. The cluster of seismicity near SFO has been persistently active for the entire time period of recording and poorly-constrained fault plane solutions for these events indicate NNW-striking right-lateral strike-slip (or, alternatively, ENE-striking left-lateral) nodal planes. The diameter of these each of these two clusters (~2 km) is comparable to horizontal location errors of these events and thus precludes detection of any real alignments within these clusters. Two of the largest events in this study (M=2.4 and M=2.9) occurred at a depth of 8 km beneath Redwood City (RC on map) and these also yielded poorly-constrained fault plane solutions with either NNW-striking right-lateral or ENE-striking left-lateral strike-slip nodal planes. In addition, a notable M=2.4 event occurred 18 km beneath San Francisco south of the Golden Gate bridge.

Recent marine high-resolution seismic profiling in the Bay revealed two Holocene fault zones, the Hunter's Point and Coyote Point fault zones (HPFZ and CPFZ on Figure 1, based on preliminary partial delineations of these fault zones from Marlow, Mann and Anima, 1993, USGS Yearbook). Both fault zones are generally NW-striking, apparently extend onshore on the peninsula, and coincide with previously identified aeromagnetic highs which extend across the Bay to the SE. The clusters of seismicity near SFO and Oyster Point, described above, are located on each side of the NW-trending Coyote Point fault zone, however, further evidence is required to determine whether this seismicity is associated with slip on faults within this zone.
Olson, Jean O., and Zoback, M.L., 1992, Seismotectonics of the San Francisco Peninsula: EOS (Transactions American Geophysical Union), v. 73, no. 43, p. 401.
Ground Motion Prediction

9930-10303

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Program Element: III

Investigations:

This project uses ground-motion recordings in the development of methods for estimating ground motion in future earthquakes with application to probabilistic seismic hazard maps, building codes, and the design of critical facilities such as dams and nuclear power facilities.

Results:

We have completed and published an update of our equations for estimating peak horizontal acceleration and response spectra incorporating data from three recent California earthquakes (Loma Prieta, 1989, Petrolia, 1992, and Landers, 1992), which provided data in the large-magnitude, close-distance range where the earlier data set was severely deficient. In addition to including the new data, we changed the site-classification system to a three-fold classification based on average shear-wave velocity to a depth of 30 m. The new site-classification system is proposed for use in the 1994 NEHRP model building-code provisions.

Reports:


Investigation and Evaluation of Liquefaction Related Ground Displacements at Moss Landing During the 1989 Loma Prieta Earthquake

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Program Element III.1

Investigations

The purpose of this research project is to investigate and characterize select sites in the Moss Landing area where permanent ground displacements due to liquefaction were observed during the 1989 Loma Prieta earthquake. At the time of this report, the significant tasks completed include the documentation and compilation of available data and records regarding liquefaction related phenomena and site conditions in the Moss Landing area, the completion of the first phase of in situ testing at select sites, and preliminary interpretations of the collected data.

Results

A variety of valuable data and records were compiled with the cooperation of individuals, agencies, and consulting firms. The Moss Landing Harbour Office and Monterey County Public Works provided topographic maps, historical photos, pertinent reports, and damage documentation covering a large portion of the Moss Landing area. Rutherford & Chekene and Woodward-Clyde Consultants have shared detailed in situ test (CPT and SPT) data and survey records covering several locations being investigated in this study. Other sources of data include (but are not limited to) Caltrans, individual property owners, USGS personnel, published literature, and several other interested researchers.

A total of 28 cone penetration (CPT) soundings with pore pressure measurements have been performed at 7 different locations including sites where lateral ground deformations ranged from negligible (less than 1/2-inch) to greater than 4 feet. In addition, shear wave velocities were measured using seismic CPT equipment in at least one CPT sounding at each of the 7 different locations.

Seven of the CPT soundings at two of the sites were located adjacent to CPT soundings that were performed prior to the Loma Prieta earthquake. These data will provide a valuable opportunity to evaluate the effects of liquefaction on CPT tip resistances, which is an important consideration in the interpretation of empirical data bases which include substantial post-earthquake data.

The first set of rotary wash borings with standard penetration testing (SPT) are scheduled for mid-January. A second series of borings will be performed during March or April.
National Strong-Motion Network: Data Processing

9920–10272

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Investigations

1. Cataloging all strong-motion records from the USGS National Strong-Motion Network.

Developing an in-house digitizing system to replace the digitization services once provided commercially via L.S. Associates in San Jose. At this time, the following earthquake records are being processed and are awaiting digitization pursuant to the completion of the new in-house digitizing system:

- $M_L$ 6.1 Joshua Tree, southern Cal. 22 April 1992
- $M_S$ 7.0, $M_L$ 6.4 Cape Mendocino, nth. Cal. 25 April 1992
  (and two aftershocks on 26 April 1992)
- $M$ 7.4 Landers, southern Cal. 28 June 1992
- $M$ 6.5 Big Bear, southern Cal. 28 June 1992

2. We are preparing a Network Operations Manager using Paradox, a commercial database software package, to assist field technicians in the sister project—National Strong-Motion Network: Operations.

3. We continue to develop the capabilities of our data processing software including a streamlined version for export to user PCs.

Results

1. Continued processing of strong-motion records, including copying and preparing records for contracted digitization and preparing ASCII tapes for distribution, via NGDC/NOAA, to outside organizations. We often supply outside organizations with small numbers of specific processed records on MS-DOS formatted disks as requested.
To assist the user in locating the positions of stations and records, we have adapted mapping software to produce relevant maps for preliminary earthquake reports and any subsequent reports needing displays of our active stations for a given area.

2. Continued work on a Network Operations Manager using Paradox. Paradox is a relational database software package which we are using to facilitate the gathering of data in the field. With the Network Operations Manager, we can enter, via portable computers in the field, data related to the installation and inspection of strong-motion accelerographs. Reports can then be easily generated with up-to-date statistics on all USGS-maintained accelerographs, including special reports for our reimbursable projects. Past histories of each station can be examined on site by technicians, enabling them to see recurring problems easily. A special report is generated, which includes the results of an epicentral distance calculating program. A table of station epicentral distances from a given event is generated for use in our preliminary earthquake reports.

3. We continue to develop the capabilities and general usefulness of the AGRAM computer programs. We use this software for our own strong-motion record processing, and we also distribute portions of it to organizations outside the Survey.

The software we distribute for PCs is a streamlined version of several older processing programs. It is easier to use and easier to install on computers other than the VAX computers that we use than are the predecessor programs. The primary processing program, named BAP, will calculate velocity and displacement from an input acceleration time series or it will calculate acceleration and displacement from an input velocity time series. The program will make linear baseline corrections, apply instrument correction, filter high-frequency and/or low-frequency content from the time series, calculate the Fourier amplitude spectrum, and calculate response spectra. It will also plot the results after each processing step.

The most immediate reason for developing and distributing this software in a form suitable for PCs was to provide processing software that would handle the 4000+ digitized strong-motion time series that we published on the Strong-Motion CD-ROM (as USGS DDS #7). The time series on the CD-ROM are in a relatively unprocessed form. They would be of little use to many of the organizations that purchase the CD-ROM unless we also distributed software than can process the data. Organizations that are collecting new strong-motion records of their own but that lack personnel with training or experience in record processing will also be more likely to process their records with satisfactory results if the USGS processing software and user's guides are available to them.
Documentation is an important aspect of this effort. The BAP User’s Manual is the sole reference given in the Strong-Motion CD-ROM for processing all its records. The User’s Manual provides processing guidelines that should be of help to those who are using software other than BAP to do the actual processing. Consequently, this documentation must cover why and when different features of BAP should be used, in addition to the nuts-and-bolts of how to use it. This software is for people who are not necessarily steeped in strong-motion record processing requirements and techniques, and that means the documentation must be very thorough. The software is also for people who are impatient with computer problems and are reluctant (or unable) to telephone the author for assistance. As such, the software and its documentation must be much more robust and thorough than software that is used only in-house.
Investigations

[1] Operate 40 creepmeters along the San Andreas, Calaveras, and Hayward faults in central California. Twenty-eight of the sites are equipped with GOES satellite telemetry for continuous monitoring. The remaining sites are read during quarterly maintenance trips.

[2] Process data to remove telemetry and manually induced errors on a quarterly basis. Maintain long-term archive of creepmeter data for use by other investigators.


Results

[1] Instruments were operational throughout the report period. In July a portable creepmeter was installed by Roger Bilham (CIRES, University of Colorado) on Claussen Ranch, north of Middle Mountain near Parkfield. The Fault Zone Tectonics project contributed telemetry equipment, and after a few false starts, the site began transmitting regularly in mid-November. This site will help us characterize fault slip north of the epicentral zone where foreshocks are expected. Preliminary data from Claussen indicate steady creep, with cumulative movement comparable to the Middle Mtn. creepmeter (XMM1), about 3 km to the southeast.

[2] The long-term creep archive is current as of November for Parkfield stations, and up to September for San Juan Bautista and Hayward stations. Data were provided to Roger Bilham (CIRES), Jim Lienkaemper (USGS), Art Sylvester (UCSB), Mike Antolik (UCB), and Imogene Blatz (SJSU) for use in a variety of studies.

Testing began to prepare creepmeter data for a coordinated Parkfield dataset. Currently the long-term creep archive is based on daily samples, processed from original 10-minute data. The goal is to recreate a clean dataset based on 10 minutes samples for each creepmeter in Parkfield since about 1986. Initial results indicate that the process is not as time-intensive as originally estimated and may even be completed within a few years time, given current staffing levels. An analysis of data from strong-motion creepmeters in Parkfield shows that at least 6 of the 7 instruments are operational, though telemetry recorders at 5 of 7 sites are not adequately tracking movement on the creepmeters.

[3] Data across the network continue to be monitored closely for changes in the rate or nature of slip. Although there were 3 B-level alerts and 1 A-level alert in Parkfield during the report...
period, there have been no significant changes in fault creep related to the seismic increase. In August creepmeters on the Calaveras fault near Hollister resumed right lateral slip for the first time since the Loma Prieta earthquake in October 1989.

The project collaborated with Roger Bilham (CIRES) and Jim Lienkaemper (USGS) to develop sites for 7 creepmeters along the Hayward fault. Although 3 installations were planned for the report period, only 1 was completed (in November 1993) due to lengthy negotiations with landowners and permitting agencies. The process is greatly impacted by a prevailing fear among property owners that a creepmeter on their land will reduce property values and render their land un-sellable. Telemetry equipment, including satellite antenna and solar panels, is also a target for vandalism. Work continues to identify sites combining fault zone clarity with diminished impact on wary landowners.

Reports published
The objectives of the Branch of Seismology Computer Center are to:

Maintain a strong capability for the processing, analysis and dissemination of all strong motion data collected on permanent and portable arrays;

Support research projects in the Branch of Seismology by providing programming and computer support including digitizing, graphics, processing and plotting capabilities as an aid to earthquake investigations;

Manage and maintain computer hardware and software so that it is ready to process data rapidly in the event of an earthquake.

The Branch facilities, include VAX minicomputers in a dual-host, clustered system, various DEC VAXstations, also clustered, all running VMS version 5.5-2. We maintain a PDP 11/73 running RSX-11M+ for GEOS playback. The project also maintains a high speed IBM RS/6000 Model 550 Graphics Workstation with 256MB of RAM, and many desktop PCs and Macs, all networked. We also support a Novell network configuration used by Branch Administrative personnel. The Project maintains peripherals such as read/write optical disks, laser printers, CD-ROM drives and various tape drives. The Branch computers are part of a local area network with other Branch, OEVE, Geologic Division, and ISD computers, and we have access to computers Survey-wide over Geonet. Project personnel join other office branches in the support of the local area network which includes sub-LANs for desktop workstations, PC's and Macs.

INVESTIGATIONS

VAX 11/785 Replacement - Project personnel planned to reconfigure devices currently attached to a VAX 11-785 system so that they would run on a smaller, more easily maintained VAX. This would allow the Survey to save power consumption costs, would restore valuable space, and would save some hardware maintenance costs.

Network Connections - We planned to connect 16 scientists' desktop computers to the LAN with high speed Ethernet connections. This would make it possible for them to send and receive electronic mail, use shared printers, file servers, and shared applications. As shared resources are made accessible, the need for personal workstations, printers, duplicate software, etc. would be reduced.
VMS Server - Many BSIS scientists use VMS on VAXes that are clustered for access to shared devices. Network access to shared printers, file services, and electronic mail is dependent upon VMS and Pathworks, a software package that allows PCs, Macintoshes, and UNIX workstations to use network services through a VMS server. We are currently using a pair of clustered MicroVAX 3300s as servers. We planned to upgrade this configuration, that is, replace at least one of the CPUs, with a mid-range DEC AXP (Alpha.) We would be able to use all of our current disks, tape drives, CD-ROM and read/write optical disks with this new server; all of our peripheral devices would be compatible. The addition of this processor would give VMS users the processing power of RISC based machines and would allow us to increase accessibility to shared services on this cluster to all scientists supported by the project.

Software Library - The project planned to maintain a software library. There are many scientific visualization, mapping and plotting packages that could be shared among scientists. Some software such as word processors and other heavily used programs are not suitable for checkout, but we could save the cost of duplicate software in some cases by keeping an inventory and sharing. We also planned to purchase a scientific visualization package to run on our shared IBM RS/6000 workstation.

Color Printer - The project currently supports a networked, high resolution dye-sublimation color postscript printer. The cost per page of the output is $2.50, so using the printer for trials before final output is unrealistic. An inexpensive, medium quality, rebuilt color printer could be made available that produces output at $.50 per page. This printer could be used for final copies in many cases, and for preview of high quality plots before they are sent to the high resolution printer.

Digitizing - The project and interested scientists investigated the possibility of installing a large format digitizing table, using software loaded on a shared Macintosh Quadra 900, to digitize waveforms, maps, etc.

Network reconfiguration - The project planned for BSIS use of a new network router to be installed by ISD.

Routine - The BSIS Computer Center routinely performs backup of all data on all "hard disk" devices on the VAX cluster and IBM RS/6000 and saves new files on a daily basis. Since many PC, Mac and UNIX users use the VAX cluster disks as file servers, they can have files backed up by storing them on this server. The most recent backups are stored off-site. Cost and space efficient DAT and 8mm tapes are used for backups. As an ongoing policy, we keep our hardware up to current revision levels, and operating system, network, and other software at the most recent versions possible.
RESULTS

As a result of these and previous investigations, the project has:

Replaced the VAX 11/785 with a VAX 8250, thus saving power, space, and maintenance costs, and is now about to replace the 8250 with a faster, less costly VAX 3300. A higher speed CALNET Project VAX has been installed in the VAXcluster maintained for general use.

With a lot of help from branch personnel outside the Computer Center project, network hardware and software was purchased and installed to integrate 20 scientists’ desktop computers into the Menlo Park LAN.

A DEC AXP Model 3000/600 has been ordered and plans are being completed for its integration into the general user VMS cluster.

We have looked at demonstration copies of scientific visualization packages for the IBM RS/6000, namely AVS and IBM Data Explorer. The packages are costly, although we can license AVS at a discount as part of a USGS site license for that software. As yet we have not permanently installed a scientific visualization package on the RS/6000. We have added USGS Digital Chart of the World and VistaPro software to our software library for checkout. Various plotting, charting, and utility programs are available on our shared 486 and Macintosh Quadra 900. A few copies of MS-DOS 6.0, Microsoft Windows 3.1, and Wordperfect are available for checkout.

Branch scientists purchased and installed a high quality, low cost, thermal wax postscript printer on the Ethernet. We have made this printer available to networked PCs and have added queues for its use on our VMScluster.

A large format digitizing table was purchased and installed with software for its use on the shared Mac Quadra 900. We also wrote instructions for its use and wrote software to use its output files to create and plot latitude/longitude data with QPLOT or other map plotting software.

We purchased and plan to install network backbone cable to a port on the new router that will isolate network traffic on the first floor of Building 8 from other traffic on the LAN.

Managed, maintained, updated Branch computer system hardware and software, and managed computer resources for other OEVE scientists.

REPORTS

The Seismology Computer Center Project reports its plans and activities routinely in annual and semiannual technical summaries.
Semi-annual Project Summary

Inventory and Preliminary Seismic Vulnerability Assessment of Essential Facilities for GIS Data Base in the Southern New Madrid Seismic Zone (East Arkansas)

Agreement No. 1434-92-G-2198  Program Element III
July 1, 1992 to June 30, 1994

T.S. Chang, H. T. Kung, and S. Pezeshk
Center for Earthquake Research and Information
Memphis State University
Memphis, TN 38152
(901) 678-2007

Research Background

Evidence from past earthquakes has shown that structural damage potential and failure during earthquakes are strongly associated with local site condition sand structural characteristics. Thus, there is a clear need to reveal the current earthquake resistant integrity of critical essential facilities to develop effective and feasible measures for reducing earthquake risk in earthquake-prone areas. The interdisciplinary study in this report is conducted to obtain information about the damage risk imposed to the existing essential facilities in the central United States from the New Madrid seismic zone (NMSZ) earthquakes. Results of the study, including a Geographic Information System (GIS), will provide information for regional earthquake preparedness and response plans for reducing risk of casualty and property loss in the event of moderate NMSZ earthquakes (M = 6 to 7). This report presents the current status of the study for the selected essential facilities (schools, fire stations, hospitals, and main river-crossing bridges) in east Arkansas.

Methods and Procedures

In this study the methodology was to develop a prioritization scheme on which to base a retrofit and replacement strategy for the study area. A preliminary screening method requires access to the seismic vulnerability inventory of all essential facilities, followed by a site investigation for seismic vulnerability assessment. In this study we used (1) the ATC-21 and (2) a preliminary seismic vulnerability index score system developed by the research at Center for Earthquake Research and Information (CERI) at Memphis State University. A technical meeting was held to discuss and finalize the CERI vulnerability evaluation system. Table 1 shows the members of the technical advisory group for the study. This system uses existing data (site, subsurface condition, foundation, and structure) and the results of a quick on-site documentation of target facilities. As shown in Table 2, a pre-determined rational weighing was assigned to each criterion according to its recognized contribution to earthquake damage of structures based on experiences from previous earthquakes and state-of-the-art knowledge in earthquake engineering. The evaluation system used in the study is cost-effective and useful for regional earthquake vulnerability assessment, which produces meaningful results for earthquake-related issues in the study area within a limited budget and a certain period of time.

This study provides feasible measures for identifying some potentially hazardous facilities that require further detailed seismic vulnerability evaluation and/or intensive maintenance. Overall current conditions of earthquakes resistant integrity of the evaluated facilities will be revealed to
Table 1. Members of the technical group attending CERI meeting

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr. James Collins</td>
<td>Director/City Engineer of Memphis</td>
</tr>
<tr>
<td>Mr. Dan Graddy</td>
<td>Deputy City Engineer of Memphis</td>
</tr>
<tr>
<td>Mr. Wade Towles</td>
<td>County Engineer of Shelby County</td>
</tr>
<tr>
<td>Mr. Edward Goksel</td>
<td>Engineer, Shelby County</td>
</tr>
<tr>
<td>Dr. Richard D. Woods</td>
<td>Professor of Civil Engineering at University of Michigan</td>
</tr>
<tr>
<td>Dr. Robert D. Hanson</td>
<td>Professor of Civil Engineering at University of Michigan</td>
</tr>
<tr>
<td>Dr. Howard Hwang</td>
<td>Professor of Civil Engineering at Memphis State University</td>
</tr>
<tr>
<td>Dr. Tzyy-Shiou Chang</td>
<td>Associate Professor of Civil Engineering at Memphis State University</td>
</tr>
<tr>
<td>Dr. Shahram Pezeshk</td>
<td>Assistant Professor of Civil Engineering at Memphis State University</td>
</tr>
</tbody>
</table>

Table 2. The Weight of Evaluation Criteria for Buildings and Bridges

<table>
<thead>
<tr>
<th>Structure Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Type</td>
<td>20</td>
</tr>
<tr>
<td>Building Age/Code Adoption</td>
<td>20</td>
</tr>
<tr>
<td>Vertical Irregularity</td>
<td>3</td>
</tr>
<tr>
<td>Soft Story</td>
<td>5</td>
</tr>
<tr>
<td>Torsion Irregularity</td>
<td>3</td>
</tr>
<tr>
<td>Plan Irregularity</td>
<td>3</td>
</tr>
<tr>
<td>Short Columns</td>
<td>5</td>
</tr>
<tr>
<td>High Rise (for hospital only)</td>
<td>5</td>
</tr>
<tr>
<td>Pounding</td>
<td>3</td>
</tr>
<tr>
<td>Heavy Cladding</td>
<td>3</td>
</tr>
<tr>
<td>Visible Damage</td>
<td>5</td>
</tr>
<tr>
<td><strong>Foundation Factor</strong></td>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td>Soil Type</td>
<td>10</td>
</tr>
<tr>
<td>Liquefaction Potential</td>
<td>10</td>
</tr>
<tr>
<td>Type of Foundation (for high or moderate liquefaction potential)</td>
<td>3</td>
</tr>
<tr>
<td>Seismic Slope Stability</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

(Chang et al., 1992)

<table>
<thead>
<tr>
<th>Structure Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superstructure</td>
<td>5</td>
</tr>
<tr>
<td>Number of Expansion Joints</td>
<td>5</td>
</tr>
<tr>
<td>Bearing Type</td>
<td>5</td>
</tr>
<tr>
<td>Alignment of the Bridge</td>
<td>5</td>
</tr>
<tr>
<td>Year Built/Code Adoption</td>
<td>10</td>
</tr>
<tr>
<td>Seismically Retrofitted (Bonus)</td>
<td>5</td>
</tr>
<tr>
<td>Classification</td>
<td>5</td>
</tr>
<tr>
<td>Height of Piers or Columns</td>
<td>5</td>
</tr>
<tr>
<td>Actual Support Length &gt; Min. Required</td>
<td>3</td>
</tr>
<tr>
<td><strong>Foundation Factor</strong></td>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td>Soil Type</td>
<td>10</td>
</tr>
<tr>
<td>Liquefaction Potential</td>
<td>10</td>
</tr>
<tr>
<td>Abutment Height</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

(Chang et al., 1992)
serve as important information for design and construction of future facilities in the study area and other earthquake-prone areas.

Data Collection of the Existing Facilities

The selected essential facilities in the study area, 10 counties in east Arkansas, include 13 regional hospitals, 94 fire stations, 174 public schools, 179 fire stations, and 49 main river-crossing bridges (see Table 3). As an example, location of the target main river-crossing bridge is shown in Figure 1. Basic data for each facility were collected through East Arkansas Emergency Management Agency, City and County governments, and private sectors. All the facility data were verified by each County's emergency management agency, board of education, fire department, and regional hospital administrator, and Arkansas Department of Transportation. The basic data related to earthquake preparedness/response for each facility include site and structure information, history, capacity, and operational information as shown in Table 4. The picture documentation of each facility will be included as part of the basic facility data.

On-Site Preliminary Seismic Vulnerability Evaluation

An engineering crew of 3 faculty and 3 students, organized into two groups, is conducting the preliminary seismic vulnerability assessment by using the collected basic facility data, picture document, and the developed preliminary seismic evaluation form. Approximately it will take 5 months to complete field examination of each individual selected facility in East Arkansas. The itemized seismic score of each evaluation factor of the facilities is also documented for future reference. The results of the evaluation reveal the technical integration of design and construction of the existing facilities in the region in terms of earthquake resistance.

It is expected to complete the field inspection by the end of February, 1994. Results of the field vulnerability assessment and the developed facility attribute files will be incorporated into the GIS system with the use of ARC/INFO and Alduss Freehand.

Published reports and papers

Several technical reports and papers related to the study were produced in previous years as follows:

Reports:


Papers:

Table 3 Selected Essential Facilities in Eastern Arkansas

<table>
<thead>
<tr>
<th>NEHRP Seismic Hazard Zone</th>
<th>Estimated Earthquake Intensity</th>
<th>County</th>
<th>Hospital</th>
<th>Fire Station</th>
<th>School</th>
<th>Bridge</th>
<th>Sub. Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>5, 6, 7</td>
<td>XI</td>
<td>Mississippi</td>
<td>2</td>
<td>14</td>
<td>30</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>XI</td>
<td>Crittenden</td>
<td>1</td>
<td>9</td>
<td>25</td>
<td>0</td>
<td>35</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>X</td>
<td>Poinsett</td>
<td>1</td>
<td>8</td>
<td>14</td>
<td>9</td>
<td>32</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>X</td>
<td>Cross</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>X</td>
<td>St. Francis</td>
<td>1</td>
<td>10</td>
<td>14</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>3, 4</td>
<td>X</td>
<td>Lee</td>
<td>0</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>IX</td>
<td>Clay</td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>4</td>
<td>23</td>
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<tr>
<td>5, 6, 7</td>
<td>IX</td>
<td>Greene</td>
<td>1</td>
<td>6</td>
<td>19</td>
<td>3</td>
<td>29</td>
</tr>
<tr>
<td>5, 6, 7</td>
<td>IX</td>
<td>Craighead</td>
<td>4</td>
<td>14</td>
<td>30</td>
<td>3</td>
<td>51</td>
</tr>
<tr>
<td>3, 4</td>
<td>IX</td>
<td>Phillips</td>
<td>1</td>
<td>13</td>
<td>17</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>13</td>
<td>94</td>
<td>174</td>
<td>49</td>
<td>330</td>
</tr>
</tbody>
</table>
### Table 4. Standard GIS data Base Format for Essential Facilities

#### Facility Element: Schools

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Name:</td>
</tr>
<tr>
<td>2.</td>
<td>Principal:</td>
</tr>
<tr>
<td>3.</td>
<td>Address:</td>
</tr>
<tr>
<td>4.</td>
<td>Telephone No.:</td>
</tr>
<tr>
<td>5.</td>
<td>Picture File No.:</td>
</tr>
<tr>
<td>6.</td>
<td>Other Identifiers:</td>
</tr>
<tr>
<td>7.</td>
<td>Main Access:</td>
</tr>
<tr>
<td>8.</td>
<td>Open Space for Emergency (Y/N):</td>
</tr>
<tr>
<td>9.</td>
<td>Basic Structural Information</td>
</tr>
<tr>
<td>(a)</td>
<td>Year Built:</td>
</tr>
<tr>
<td>(b)</td>
<td>No. of Buildings:</td>
</tr>
<tr>
<td>(c)</td>
<td>Floor Area of Each Building:</td>
</tr>
<tr>
<td>(d)</td>
<td>Total Floor Area:</td>
</tr>
<tr>
<td>(e)</td>
<td>Stories of Each Building:</td>
</tr>
<tr>
<td>(f)</td>
<td>Structural Type of Each Building:</td>
</tr>
<tr>
<td>(g)</td>
<td>Architect/Designer:</td>
</tr>
<tr>
<td>(h)</td>
<td>Seismic Code Adoption (Y/N):</td>
</tr>
<tr>
<td>(i)</td>
<td>Foundation Type (Deep/Shallow):</td>
</tr>
<tr>
<td>(j)</td>
<td>Liquefaction Potential (H/M/L):</td>
</tr>
<tr>
<td>(k)</td>
<td>Seismic Soil Type (SL2/SL3/SL4):</td>
</tr>
<tr>
<td>10.</td>
<td>Basic Education Program Information:</td>
</tr>
<tr>
<td>(a)</td>
<td>Capacity:</td>
</tr>
<tr>
<td>(b)</td>
<td>Enrollment:</td>
</tr>
<tr>
<td>(c)</td>
<td>School Hours:</td>
</tr>
<tr>
<td>(d)</td>
<td>Average Daily Attendance:</td>
</tr>
</tbody>
</table>

#### Facility Element: Fire Station

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Name</td>
</tr>
<tr>
<td>2.</td>
<td>Chief:</td>
</tr>
<tr>
<td>3.</td>
<td>Address:</td>
</tr>
<tr>
<td>4.</td>
<td>Telephone No.:</td>
</tr>
<tr>
<td>5.</td>
<td>Picture File No.:</td>
</tr>
<tr>
<td>6.</td>
<td>Other Identifiers:</td>
</tr>
<tr>
<td>7.</td>
<td>Main Access:</td>
</tr>
<tr>
<td>8.</td>
<td>Open Space for Emergency (Y/N):</td>
</tr>
<tr>
<td>9.</td>
<td>Basic Structural Information</td>
</tr>
<tr>
<td>(a)</td>
<td>Year Built:</td>
</tr>
<tr>
<td>(b)</td>
<td>No. of Buildings:</td>
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<tr>
<td>(c)</td>
<td>Floor Area of Each Building:</td>
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<tr>
<td>(d)</td>
<td>Total Floor Area:</td>
</tr>
<tr>
<td>(e)</td>
<td>Stories of Each Building:</td>
</tr>
<tr>
<td>(f)</td>
<td>Structural Type of Each Building:</td>
</tr>
<tr>
<td>(g)</td>
<td>Architect/Designer:</td>
</tr>
<tr>
<td>(h)</td>
<td>Seismic Code Adoption (Y/N):</td>
</tr>
<tr>
<td>(i)</td>
<td>Foundation Type (Deep/Shallow):</td>
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<tr>
<td>(j)</td>
<td>Liquefaction Potential (H/M/L):</td>
</tr>
<tr>
<td>(k)</td>
<td>Seismic Soil Type (SL2/SL3/SL4):</td>
</tr>
<tr>
<td>10.</td>
<td>Basic Fire Fighting Facilities:</td>
</tr>
</tbody>
</table>

#### Facility Element: Hospital

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>1.</td>
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<tr>
<td>2.</td>
<td>Contact Person:</td>
</tr>
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Figure 1. Location of main river-crossing bridges in east Arkansas
Report and paper for current study in 1993-1994

The final report of the project for FY 1993 and technical papers resulting from the project will be prepared for publication in 1994-1995. The final report of the project will be submitted to the USGS as indicated in the proposal.
GEOLOGIC AND GEOTECHNICAL CHARACTERIZATION OF THE WEEKS CREEK LANDSLIDE, SAN MATEO COUNTY, CALIFORNIA

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Los Gatos, California 95030
(408) 354-5542

Element III.3

INVESTIGATIONS

This progress report discusses a partly completed study involving earthquake-triggered landsliding and landslide prediction methodology. Earthquake-triggered slope instability results in damage to structures and facilities located in hillside regions that are subjected to strong seismic ground motion. In previous studies, we and others have found that analytical methods of modeling slope stability are highly sensitive to several factors, specifically: (1) shear strength of the rupture surface materials; (2) geometry of the landslide mass; (3) influence of ground water and pore-water pressures; and (4) strong ground motion felt by the landslide. The accuracy of slope stability calculations are dependent on an accurate determination of the values for these parameters.

The objectives of this study are to characterize and analyze geologic and geotechnical conditions of the Weeks Creek landslide, which is an active landslide located on the San Francisco Peninsula in San Mateo County, California (Figure 1). This landslide provides an excellent opportunity to examine the parameters that affect earthquake-triggered ground failure for the following reasons: (1) the landslide has a long history of previous landslide movement; (2) the landslide lies in a tectonically active region and is highly susceptible to strong seismic ground shaking generated by any of several nearby faults; and (3) the landslide currently hosts ground motion instrumentation installed by the U. S. Geological Survey.

The primary goal of our study is to establish a well-characterized, intensely instrumented active bedrock landslide in the San Francisco Bay Area, in which the variables in landslide stability models have been reduced as much as possible. Armed with site-specific values for landslide parameters (as determined from this investigation), we can then make a prediction of future landslide behavior, and subsequently compare the predicted behavior with actual landslide behavior during future earthquakes. The establishment of test sites such as the Weeks Creek landslide are also part of a wider effort to assimilate a database that can be used to record site specific ground motions and constrain landslide prediction methodology.

RESULTS

Geologic Setting of the Weeks Creek Landslide - The Weeks Creek landslide complex is situated approximately 4 km north of the community of La Honda along State Highway 84 in southern San Mateo County, California (Figure 1). The landslide is in the northern Santa Cruz Mountains, a rugged and steep range that is susceptible to strong ground shaking from earthquakes originating on many active faults in the region. The San Andreas fault (4 km to the northeast) and San Gregorio fault (12 km to the southwest) are the closest major active fault systems to the landslide (Brabb and Olson, 1986). The landslide and vicinity are underlain by tightly folded, Tertiary sedimentary bedrock of the San Lorenzo Formation (generally Eocene to
Oligocene). Surrounding ridges, including portions of the landslide headscarp and side scarps are capped by the resistant Mindego basalt (Oligocene and Miocene).

The Weeks Creek landslide is an ancient, dissected landslide mass that is approximately 1,000 m long, 400 m wide and on the order of 40 m deep (16 million cubic meters). This landslide is portrayed on the regional geologic map prepared by Wentworth and others (1985) and is readily visible on stereoscopic aerial photographs of the area. A portion of the landslide complex has moved somewhat continuously for at least 100 years. The landslide moved about 3 feet during 1906 earthquake event (movement is referenced in Lawson and others, 1908). The historically active, reactivated portion of the ancient landslide is approximately 500 m long, 200 m wide, and approximately 15 m deep (1.5 million cubic meters).

**Previous Work** - According to Youd and Hoose (1978), a portion of the Weeks Creek landslide moved in response to the 1906 San Francisco earthquake. Descriptions of the landslide movement in Lawson (1908) imply that pre-1906 landslide movement may have also occurred. Close (1969) and Wieczorek (pers. comm.) have indicated other episodes of limited movement in response to elevated pore-water pressures. We infer from aerial photograph interpretation, and an interview with the property owner, that a 10-m-high scarp associated with the active portion of the landslide has enlarged vertically approximately 5 m since about 1955. According to the property owner, landslide movement appears to have accelerated in response to the 1992-1993 winter rains.

The U. S. Geological Survey conducted a limited geotechnical study of the landslide from about the mid-1970s to the mid-1980s. Adam (1975) extracted a core of sediments from a depression in the upper surface of the ancient landslide and performed pollen analyses and radiocarbon dating. The results of this work indicated that the ancient landslide mass had been relatively stable for the past 3,000 years, but that two possible landslide events may have occurred prior to 3,000 years ago. Additional work by Gerald Wieczorek (U. S. Geological Survey) included mapping of surficial features and monitoring of piezometers, inclinometers and extensometers in the active portion of the landslide. Landslide movement was measured following the wet winters of 1981-1982 and 1982-1983 (Wieczorek, pers. comm.). In 1981, the U. S. Geological Survey drilled 5 small-diameter borings and collected three samples that were tested for grain size distribution and direct shear (strength) measurements. Although these samples were probably not from rupture surface materials, the data provide a preliminary representation of landslide characteristics. Wieczorek has provided us with a topographic base map prepared for the U. S. Geological Survey from aerial photography in 1983.

**Critical Landslide Characteristics** - Parameters necessary for seismic slope stability analysis include: 1) landslide dimensions (geometry), usually analyzed as a representative cross section; 2) shear strength and density parameters for the basal rupture surface materials and the landslide mass, respectively; 3) ground water levels or pore-water pressures acting on the landslide, usually considered as a phreatic surface; and 4) earthquake ground motions affecting the landslide, usually input as a seismic coefficient. In addition, the actual amount of displacement that a landslide experiences in response to seismic shaking provides constraints on "cumulative displacement" analytical methods, which are used to predict the amount of landslide displacement.

**Current Work** - The specific tasks of this study are to determine: (1) the depth and geometry of the actively moving portion(s) of the landslide; and (2) the geotechnical properties of pertinent earth materials (landslide mass and rupture zones). We also initially planned to install borehole accelerometers to measure seismic ground motion in bedrock materials at depth, and thus complement the U. S. Geological Survey's instrumentation at the site. Thus, we had planned to acquire the entire set of parameters needed to analyze the mechanics of
earthquake-triggered landsliding will be acquired and be available for input into stability analyses. Because of reduced funding, we were not able to purchase the borehole accelerometer. After discussing options with the U. S. Geological Survey, it was decided to complete a sufficient characterization of the landslide so that instruments could be installed at suitable sites and depths in the future.

To date, our work has included:

- Compilation and review of State Highway 84 repair records from the State of California Department of Transportation (Caltrans) to help us date and bracket past periods of movement for correlation with records of rainfall and earthquake shaking;
- Geomorphic mapping to determine landslide boundaries and areas of possible incipient movement;
- Geologic mapping of the vicinity to investigate the influence of stratigraphy on development of basal rupture zones;
- Downhole logging of two, 24-inch-diameter boreholes (drilled to depths of 35 m and 28 m, respectively) to directly observe, sample, test and evaluate the depths and characteristics of the ancient and active landslides and associated ground-water conditions;
- Seismic refraction survey of the landslide and correlation of geophysical results to surface measurements and subsurface observations;
- Laboratory testing of samples extracted from the boreholes to determine geotechnical properties of critical materials; and
- Installation of "poor-man" inclinometers to gather crude measurements of landslide movement.

In addition to the above work, the U. S. Geological Survey (Harp and Jibson, unpublished) has installed instrumentation, including accelerometers, extensometers and piezometers at two locations (on and off the actively moving portion of landslide).

The depth of the ancient landslide was encountered at depths of 32 m and 25 m in boreholes LD-1 and LD-2, respectively (Figures 2 and 3). Preliminary findings indicate that the depth of the ancient landslide is controlled, in part, by local stratigraphy. Correlation of roadcut exposures to subsurface observations indicate, preliminarily, that the basal rupture zone has developed within weathered diabase dikes and that sliding of a sequence of Tertiary sedimentary rocks took place along this contact. If this relationship is confirmed by further study, then it would provide some guidance in evaluating regional landslide conditions. We encountered an active rupture surface at depths of 10 m and 13 m in LD-1 and LD-2, respectively. Extrapolation to the center of the landslide, as determined from seismic refraction and geologic field mapping and profiling, indicates that the maximum depth of the active portion is on the order of 15 m. Evidence of other deeper, and currently dormant, landslides also were observed in the boreholes.

REPORTING

We are currently about 9 months into our 12-month study, and have not yet published any investigative results. We have completed most of the field investigation portion of our study and are currently conducting geotechnical laboratory testing of earth materials. We anticipate that all testing and analysis will be completed by the end of our project period (March 31, 1994).
References Cited


Close, P. H., 1969, Weeks Creek Landslide: research report for Master's Degree, Stanford University (A. M. Johnson, instructor), Stanford, California, 12 p.


Figure 1. Location of the Weeks Creek landslide in relation to major active faults.
ANCIENT WEEKS CREEK LANDSLIDE

POSSIBLE UPSLOPE EXTENSION OF ACTIVE LANDSLIDE

ACTIVE WEEKS CREEK LANDSLIDE (Historic Reactivation)

Figure 2. Generalized map of the Weeks Creek landslide complex showing the ancient and active portions of the landslide, locations of boreholes LD-1 and LD-2 (circles), instrumentation sites (squares), and geologic cross section A-A'.
Figure 3. Simplified geologic cross section A-A' along the axis of the Weeks Creek landslide.
INVESTIGATIONS

The objectives of this project are to better understand the mechanics of crustal earthquakes, to characterize fault properties relevant to the earthquake process in the form of constitutive laws and to apply those results to theoretical modeling of various earthquake phenomena. Investigations in the past year emphasized the following three topics.

1) Experimental investigation of micro-mechanical processes that cause the characteristic state-dependence of fault sliding effects.
2) Fault sliding experiments at hypocentral conditions including hydrothermal processes and elevated temperatures.
3) Development and application of a constitutive formulation relating stressing history to rate of earthquake activity.

RESULTS

1) Micro-mechanical processes controlling fault friction. (Dieterich, Kilgore and Blanpied) Sliding memory effects (i.e. slip weakening, time-dependent healing and various transient slip speed effects) are characteristic of rock friction and are well represented as a state-dependence in fault constitutive formulations. These constitutive formulations are widely employed in analysis of laboratory experiments and for modeling of the earthquake instability process, but underlying micromechanical processes have eluded definitive explanation. We continued to develop and apply a new technique for direct quantitative microscopic observation of sliding surfaces during friction experiments to better understand the micro-mechanical processes that cause sliding memory effects. The technique employs transparent materials. When roughened surfaces are brought into contact under stress and viewed through a microscope using transmitted illumination, regions in actual contact appear as bright spots against a dark background of scattered illumination. From
observations of changes in contact parameters during slip we have established that state-
dependence of frictional processes arises from time-dependent growth of contact area. In
addition, we are able to quantitatively model the observed displacement-dependent
evolution of friction using measured contact size distributions.

2) Sliding experiments at hypocentral conditions (Blanpied) An ongoing experimental
program with David Lockner and Jim Byerlee continued to investigate the behavior of
faults at hydrothermal conditions. Analysis of the results of an extensive suite of friction
experiments is near completion. Sliding experiments performed at the highest temperatures
and lowest slip rates showed that solution-transport of material can form a strong, self-
generated seal which isolates the deforming fault from the nearby country rock. This seal
prevents overpressured fluids from escaping from the compacting fault, thus allowing slip
at low resolved shear stress. This result is consistent with recent models to explain
inferences of low fault strength, and has motivated new theoretical models to explain the
kinematics of earthquake cycles.

The design of a heated sample enclosure for the direct-shear friction apparatus was also
completed and tested in collaboration with Brian Kilgore and machinist Dennis Mello.

3) Simulation of seismic activity. (Dieterich) A general state-variable constitutive
formulation for rate of earthquake production resulting from an applied stressing history
has been derived employing solutions for nucleation of earthquakes with rate- and state-
dependent fault strength. It is found that that various features of earthquake clustering may
be modeled as arising from sensitivity of earthquake nucleation times to the stress changes
induced by prior earthquakes. The model gives the characteristic Omori aftershock decay
law and assigns physical interpretation to aftershock parameters. Earthquake data appear
to support a model prediction that aftershock duration, defined as the time to return to the
background seismicity rate, is proportional to mainshock recurrence time. Observed spatial
and temporal clustering of earthquakes arise from the spatial dependence of stress changes
of prior earthquakes and time- and stress-dependent nucleation. Initial tests of the
formulation to invert temporal variations of earthquake rates for changes in driving stress
were begun.

A collaborative study with Paul Okubo was initiated in part to apply the inversion
method to seismic activity in the south flank of Kilauea Volcano. In organizing data for
this investigation we observe an unusual pattern of recurring seismic quiescence from the
Kalapana region of the south flank of Kilauea volcano on the island of Hawaii. Statistically
significant intervals of seismic quiescence preceded the Kalapana earthquakes of 1975
(M7.2) and 1989 (M6.1) and a third interval of quiescence is underway at present.
Interpretation of the episodes of quiescence is complicated by the sensitivity of flank
seismicity to the continuing magmatic activity in the adjacent east rift zone of Kilauea. The
current episode of quiescence may be caused by alteration of magmatic processes in the east
rift zone or by precursory changes to another Kilauea flank faulting event. A paper
describing these observations was submitted for review at the end of FY-93.
REPORTS


Abstracts


Objectives

Under this project we are installing a four-station accelerometer network in the urban, high-risk areas of Memphis-Shelby County. The CERI-designed gain-ranging instrumentation is capable of recording waveforms of regional earthquakes from background noise level to signal strength of 1.0 g. Pending completion of the network, the additional objective is to characterize the seismic motion expected from large New Madrid earthquakes by study of the most relevant existing recordings.

Project Status

The four gain-ranging accelerometer (GRA) stations will be colocated with facilities of Memphis State University, Memphis Light, Gas and Water Division, and the Shelby County Board of Public Utilities, as shown in Figure 1. At each station will be a three-component force-balance accelerometer, a PANDA II four-channel gain-ranging processor and radio telemetry. This means that each station will normally operate at high gain, but channels 1 to 3 (ground accelerations) switch individually to lower gains without data loss when strong signals arrive. Exact waveforms are recovered by gain information encoded on channel 4. This technology is proven in field operation. Signals received at CERI will be digitized in a PC-based network acquisition system.

The President’s Island location (Figure 1, westernmost station), is the noisiest due to nearby industrial activity and weak soil. Thus, this station will generate relatively few usable regional earthquake seismograms. Nevertheless, it seems important to compare President’s Island data with that of other Memphis locations since this industrial area, on an engineered fill, may be the most vulnerable in Memphis to regional earthquakes.

Most of the network field and laboratory hardware has now been built or assembled, but field installation is still several months off due to many prior commitments of the CERI instrumentation group. In fact, PANDA II processor units were fabricated and tested in larger batches of equipment being built for similar field projects. While this delay is regrettable, there will be no compromise of the system performance envisioned in the proposal. The project also benefits from network acquisition and archiving software designed to handle the larger regional cooperative networks in which CERI participates.
Thus, data recorded by this network will fill an information gap left by standard strong-motion accelerographs installed in Memphis many years ago which have never been triggered. Useful information on Memphis ground motion will come from the frequent events of nearby seismic zones, many of which drive local high-gain seismographs off-scale without triggering the strong motion stations. Project instrumentation is designed to cover the dynamic range between these two existing types of seismographs. We expect to fill this gap with earthquake data directly relevant to seismic hazards of the urban area.

**Current Investigations**

Meanwhile, we have analysed seismograms and modeled the surface wave dispersion of the magnitude 4.6 Risco, Missouri earthquake of May 3, 1991 (Figures 2 and 3). Being the largest event ever recorded locally on broad-band and long-period instruments, the Risco earthquake produced low-frequency Love waves lasting for 6 minutes at Memphis. A manuscript by Dorman and Smalley is in review. The results show the effect of a shallow waveguide on three low modes of surface waves (Figure 4), and in particular the critical role of the shallowest unconsolidated deltaic sediments in determining the amplitude and frequency characteristics of these seismic arrivals. Similar effects should apply to higher mode (overtone) propagation to be investigated next.

Shallow refinement of the model waveguide (Figure 5) which adequately represents the characteristic low-frequency dispersion is expected in turn to explain with fair accuracy the higher-frequency features of the complex and strong Risco S-wave group. The Risco S-wave drove regional high-gain seismographs off-scale, but did not trigger standard strong-motion accelerographs in Memphis. However, S was well-recorded by strong-motion stations at shorter epicentral distances. These data are to be analysed and modeled in a thesis project at CERI. We are therefore approaching an understanding of the propagation effects which will facilitate deterministic waveform modeling of the elastic response to hypothetical New Madrid earthquakes.

**Publication**

Figure 1. Sites for four high-dynamic-range seismograph stations in Memphis-Shelby County. Engineering soil classifications S2, S3, and S4 denote areas of moderate to poor soil conditions with respect to potential earthquake damage.
Figure 2. Epicenter of the magnitude 4.6 Risco, Missouri earthquake of May 4, 1991, and 159 km path to the broadband and long-period stations at CERI. Isopach contours give the thickness (in feet) of the low-velocity Cretaceous-Tertiary-Quaternary embayment clastics layer.

Figure 3. Broad-band and long-period seismograms of the Risco earthquake recorded at CERI. As at other high-gain seismograph stations, the S-wave drives the traces off-scale. The long Love wave train, well-recorded on the LPEW and GURH1 components, lasts for about 6 minutes. For larger magnitude earthquakes, the strength of the low-frequency Love waves will increase relative to the strength of S.

Figure 4. Points represent group velocity dispersion analysis of the low-frequency wave groups of Figure 3. The model curves (solid lines) which fit the Risco wave groups reasonably well govern the frequency and travel time relationships of waves traversing paths within the New Madrid seismic zone.

Figure 5. Compressional and shear velocity model for the embayment path of Figure 1. This layered velocity structure fits the sonic log velocities at the Haynes well and also fits the characteristic surface wave dispersion of Figure 4. These physical properties define the hazard of amplified low-frequency shaking from a regional earthquake.
Analysis of Digital Waveforms in the Northeastern U.S. for Source Depth and Strong Ground Motion Information

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Program Element III.2

Investigations

The purpose of this research is to analyze the waveforms of locally recorded earthquakes in the northeastern U.S. to better determine the source depth and the propagation of strong ground motions across the region. The investigation involves three tasks: (1) searching for free-surface reflections in the local waveforms to help constrain the earthquake focal depths, (2) studying the amplitudes of P and S phases at about 100 km distance from the sources to see if any amplification due to post-critical Moho reflections may be present, and (3) studying the distance attenuation of the spectral components of the ground motions in the region with application to spectral seismic hazard maps. This research uses data from the New England Seismic Network operated by Weston Observatory of Boston College.

Data Analysis

Thus far the primary effort has been put forth toward the first two tasks. These tasks are related in that some identification of post-critical Moho reflections is necessary in the local seismograms before the free-surface reflections can be sought (i.e., one does not want to misidentify a Moho reflection as a free surface reflection). The method of analysis has been to follow several processing steps on the data from several earthquakes. The first is to assemble all of the available waveforms in the distance range from 50 km to about 300 km from the events. For each waveform beyond 90 km an estimate is made of the expected arrival time of the PmP phase, and the record is then examined to see if the PmP phase can be identified. Next the individual stations are put on a single plot and aligned along the first P wave arrivals. This plot is then investigated to see if any free-surface reflections can be identified. Finally, these aligned waveforms are processed by having their absolute values taken (to ensure
that polarity changes do not strongly mask later phases which have a common arrival time relative to the direct arrival, and the absolute value waveforms are stacked. The intent of this processing is to enhance free-surface reflections, which should arrive at all head-wave distances approximately the same time after the first head-wave arrival.

Preliminary Results

The results so far have been very mixed. Of four earthquakes which have been processed, one (June 17, 1991 in New York state) has a well-determined focal depth of about 13 km, while the other events have poorly determined focal depths. However, these latter three are all suspected to have depths of 6 km or less. All of the events show possible free-surface reflections, but these phases are not very coherent from station to station for a single event. Figure 1 is an example of the results from the processing method described above for an earthquake at Franklin Fall, NH on October 6, 1992. The stacked absolute-value trace (top) does some increase in amplitude at a time of 2.5 seconds (1.5 seconds after the first P arrivals), but several of the individual traces (IVT, DVT, TRM, and BNH) seem to have a stronger, lower frequency arrival at about 2.25 sec. In either case, if these are crustal head waves from the free-surface P reflection, then the focal depth of the event must be about 4 km or so.

Some of the records gathered so far have strong PmP phases near the expected critical distance for that phase. However, other records where a strong phase might be expected show no strong arrival at the proper time. Insufficient data have been collected at present to determine if this is due to spatial variations of the reflectivity of the Moho or due to source radiation properties.

Future Investigations

The work is continuing on the above stated tasks as planned. As the work on the first two tasks reaches its finishing stages, the primary research efforts will be turned toward the third task. No significant problems in completing this research effort is anticipated.
Figure 1. Absolute value traces of the P-wave seismograms for several New England Seismic Network stations of an earthquake on October 6, 1992 at Franklin Fall, NH. The seismograms have all been aligned at the P-wave first arrival times, and the sum of these traces is shown at the top of the figure.
The Strong-Motion Program (NSMP) in cooperation with federal, state, and local agencies and advisory engineering committees, designs, develops, and operates an instrumentation program in 41 states and Puerto Rico. Program goals include: (1) recording of potentially damaging ground motion in regional networks, and in closely spaced sensor arrays; and (2) monitoring the structural response of buildings, bridges and dams using sensors placed in critical locations. The present cooperative network consists of approximately 1,000 recording units installed at 635 ground sites, 31 buildings, 6 bridges, 57 dams, and 2 pumping plants.

**New Instrumentation**

**Structures - extensive instrumentation**

1) Olympia, WA  
Washington State Department of Natural Resources Building, six-story steel frame building with two sub-grade parking levels. 15 structural sensors plus 3 remote ground sensors.  
This project was a cost sharing cooperative program with the Division of Geology and Earth Resources.

2) Portland, OR  
Clackamas bridge crossing, Interstate 5 at Milwaukee, OR, just south of Portland. 9 structural sensors plus 3 free-field ground sensors.  
This project was funded by the Oregon Department of Transportation.

3) Newport Beach, CA  
Twin seven-story buildings with 12 structural sensors. System was renovated and sensors relocated to present day standards. Instrumentation was provided by the building owner and an operating agreement arranged through Brandow & Johnston Associates.

**Dam station**

1) Little Dell Dam, UT - Corps of Engineers  
2) Skinner Dam, CA - Metropolitan Water District of Southern California
Ground stations

1) Alaska
   Anchorage area  5
   Juneau  1
   Removals: Portage, Ski Lodge, Federal Building

2) San Bernardino, CA array - USGS  2

3) Hawaii
   Maui  1
   Lanai  1
   Oahu  3
   Project funded by the Hawaii Civil Defense

4) Philadelphia, PA - Drexel Inst. - USGS  1

5) Little Dell Dam, UT - Corps of Engineers  5

6) Pearisburg, VA - USGS  1

8) Olympia, WA - USGS  1
   Ground station for instrumented building

Earthquake Records

1) Scotts Mills, OR  M=5.7  3/25/93
   9 ground and dam records from Corps of Engineers, Veterans Administration and
   USGS stations.
   Peak ground acceleration, .06 g at Detroit Dam.

2) Anchorage, AK  ML=5.2  5/18/93
   21 ground and building records from Municipality of Anchorage and USGS
   stations.
   Peak ground acceleration, <.05 g.

3) Klamath Falls, OR  ML 5.9,5.9  9/20-21/93
   11 ground and dam records from Corps of Engineers stations.
   Peak ground acceleration, <.05 g.

Projects in planning or underway

1) Oregon
   Instrument three bridges with the Oregon Department of Transportation.

2) San Francisco
   Plan and install 36 sensor digital recording system in the U.S. Court of Appeals
   and Post Office building under renovation, including a base isolation system.

3) Ground motion arrays under further development - all sites selected
   White Mountain gap Nevada
   San Bernardino, CA Array
   San Francisco Bay Area, CA
   Seattle, WA (with advisory committee)
   Hawaii
   Eastern/Central U.S. city network


The Klamath Falls, Oregon, Earthquake Sequence of September 20-21, 1993, Dennis Johnson, 1 P.
Regional and National Seismic Hazard and Risk Assessment
9950-10025

A. Frankel, S.T. Algermissen, P. Thenhaus, D. Perkins, E.V. Leyendecker, M. Hopper,
S. Hanson, N. Dickman, B. Bender

Branch of Earthquake and Landslide Hazards
U.S. Geological Survey
MS 966, Box 25046
Denver Federal Center
Denver, CO 80225
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Program goal: III

Investigations

1. We continued our efforts with the Building Seismic Safety Council concerning the ground motion and design value maps to be used in the 1994 NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings. This involved leadership of and participation in technical subcommittees and the preparation of text for the provisions (Algermissen and Leyendecker).

2. We produced new probabilistic ground motion maps for the Pacific Northwest to evaluate the effects of differing assumptions of the rate of great earthquakes in the Cascadia subduction zone (Perkins and Hanson).

3. We are developing new ground motion hazard maps (probabilistic and deterministic) for California based on geologic slip rate data, historical seismicity, and detailed maps of surficial geology (Frankel and Thenhaus).

4. Analysis of seismograms from dense arrays installed in San Bernardino Valley of the Landers-Big Bear aftershocks to study basin response effects (Frankel).

5. Development of a new simplifies method for summing seismograms of small earthquakes to produce site-specific time histories of strong ground motions for large earthquakes with magnitudes of about 7 (Frankel).

6. Compilation of intensity data for Central U.S. earthquakes into an atlas/data base (Hopper).

Results

1. The process of producing the 1994 NEHRP provisions is continuing. No consensus has been reached yet in the BSSC committees concerning the use of ground motion and design value maps in the provisions.

2. The new ground motion maps for the Pacific Northwest show higher values along the coast when the subduction zone is assumed to fill with M8.5 earthquakes every 50 years, as opposed to the previous map where one M8.5 event was assumed to occur every 500 years.
Maps with one M9.2 event every 500 years produced probabilistic ground motions somewhat less than the case with filling the subduction zone with M8.5 events every 500 years.

3. We have produced new probabilistic and deterministic ground motion maps for the San Francisco Bay and San Bernardino Valley regions. The maps are strongly influenced by the spatial distribution of geologic units. In general, the probabilistic ground motions (0.3 sec pseudo spectral acceleration; 10% probability of exceedance in 50 years) are intermediate between deterministic maps with the mean and mean plus one standard deviation.

4. Analysis of the dense array data in San Bernardino Valley shows the presence of long-duration surface waves produced by conversion of S-waves incident at the edge of the basin. These basin surface waves propagate in a variety of directions across the Valley and are apparently reflected from the basin edges.

5. The new summation procedures successfully models the observed spectra and acceleration records of the Loma Prieta (M7.0) and Landers (M7.2) mainshocks using aftershock (M3-4) recordings.

6. Intensity data for earthquakes around New Madrid have been compiled into a computer-accessible atlas.

Reports


Near-Surface Lithologic and Seismic Properties
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Program Element: III

Investigation:
Measurement of seismic velocity and attenuation to determine the effect of local geology
on strong ground motion and to aid in the interpretation of seismic source parameters.

Results:

1. Since last report, we have finished the interpretation of borehole data (seismic velocities
and geologic logs) at eight additional strong-motion stations that recorded the Loma
Prieta earthquake. These stations are operated by the California Strong-Motion
Instrument Program (SMIP). This is the second in a series of four reports to be
published in the USGS Open-File format (see reports below).

2. We continue the interpretation (seismic velocity and attenuation) of borehole data from
the San Francisco and Los Angeles Regions.

Reports:

and geologic logs from borehole measurements at eight strong-motion stations that
recorded the Loma Prieta, California, earthquake, *U.S. Geological Survey Open-File
Report* 93-376.

The attenuation of seismic shear waves in Quaternary alluvium in Santa Clara Valley,
SIMULATING THE 3D BASIN RESPONSE IN THE PORTLAND AND PUGET SOUND REGIONS FROM LARGE SUBDUCTION ZONE EARTHQUAKES

1434-93-G-2327
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Investigations

The purpose of this project is to understand the effect of lateral variations in shallow crustal structure on expected strong ground motions in the Pacific Northwest from subduction zone earthquakes. This work begins with an analysis of strong motion recordings from the 25 April 1992 Cape Mendocino earthquake and its aftershocks as observed in the epicentral region. Although this event did not produce strong motions in Portland or Puget Sound, there is good evidence that it occurred on the shallow Cascadia plate interface, making it the first recorded Cascadia subduction event. In addition, the presence of strong motion recording stations within the Eel River basin provides the opportunity to test the procedure for modeling the long-period (1 to 10 sec) basin response for shallow subduction zone earthquakes (Figure 1).

Ground motions will be simulated using an interfacing technique which couples the analytic response from a finite fault with a 3-D finite-difference calculation for the basin response. The simulation technique will first be tested against the Cape Mendocino earthquake data. It will then be applied to calculate the long-period basin response in the Portland and Puget Sound regions from hypothetical earthquakes on the Cascadia subduction interface. Slip models and hypocenter locations will be varied to test the basin response to asperity distribution and directivity effects. The intended products of these simulations will include maps of the ground motion response throughout the Portland and Puget Sound regions for various earthquake scenarios, as well as maps showing the expected durations of strong ground motion in these regions for each of the simulated events.

Results

The 1992 Cape Mendocino earthquake is the first Cascadia subduction event to occur in historic times. This event was well recorded in the epicentral region and the data provide us with a unique opportunity to study source and wave propagation characteristics specific to the Cascadia Subduction Zone. The focal mechanism of the event indicates nearly pure thrust motion on a northerly striking fault plane having a shallow dip to the east (Oppenheimer et al., 1993). Strong motion recording sites at Petrolia, Cape Mendocino, and Bunker Hill are all located on hard rock directly above the fault plane and much of the waveform information in these records is related to the details of the earthquake source (Figure 1). Further to the north, several other strong motion recording stations were located atop the sediments of the Eel River basin (Figure 1). This structure is an east-west trending river valley with sediments reaching depths of about 600 m. The basin recordings are richer in long period energy and exhibit much longer durations
than the hard rock recordings. Record sections of the observed velocity recordings to the north of the epicenter suggest that these effects are related to surface waves which are generated at the near-source margin of the Eel River basin (Figure 2). These surface waves then propagate northward across the basin with a slow apparent velocity, leading to the long durations which are observed at the basin sites. The surface waves are most noticeable on the east-west component of motion, indicating that they are probably dominated by SH wave energy. In order to investigate these wave propagation effects in more detail, we are performing 2D and 3D elastic finite-difference calculations for models of the Eel River basin. Preliminary results of the numerical calculations indicate that the observed effects are related to the trapping and focusing of seismic energy within the basin sediments. In addition, it appears that the direct S-wave observed at the basin sites is controlled primarily by the earthquake source, while the surface waves are most sensitive to the structure and geometry of the underlying basin.

References

1992 Cape Mendocino Earthquake

Figure 1. Map of the epicentral region of the 1992 Cape Mendocino earthquake. The star indicates the epicenter and the dark shaded region is the assumed rupture plane as inferred from aftershock distribution and geodetic modeling (Oppenheimer et al., 1993). The light shaded region to the north of the fault plane indicates the location of the Eel River basin.
Figure 2. Three-component velocity recordings of the 1992 Cape Mendocino earthquake. These data have been low-pass filtered at 1 Hz. The dashed line indicates the arrival time of the direct S wave. The solid line indicates arrivals with a slow apparent velocity which are seen only at sites located in the Eel River basin.
Investigations undertaken:

Shaking Thresholds For Landslides

Data from southern California strong-motion networks have been compared to the areal limits of landslide occurrence to determine what levels of seismic shaking are necessary to trigger landslides. Arias intensities, calculated from strong-motion records from the 1987 Whittier Narrows and Superstition Hills earthquakes have been compared to the limits of rock falls from these two earthquakes to see what Arias-intensity levels were near the rock-fall limits. Similar data from the 1989 Loma Prieta earthquake in the San Francisco Bay area has been used to study Arias-intensity thresholds near both rock-fall and larger rotational-slump or block-slide limits.

Several moderate earthquakes within the Colorado Plateau have been studied because of their triggering of rock falls and rotational slumps/block slides at extreme epicentral distances.

Conducted field investigation to determine source of slope-failure event recorded as seismic signal on monitoring network at Mt. Lassen, California.

Perfomed reconnaissance of area affected by the September 20, 1993, Klamath Falls, Oregon, earthquake sequence.

Rockfall Susceptibility

Criteria for seismic rockfall susceptibility have been developed for both regional and site-specific application. Regional criteria have been formulated to allow slopes and
Ill materials to be categorized in a generalized regional sense to provide for large area overview in terms of the potential hazard from rockfall hazard. Site specific criteria have been developed and calibrated against past earthquake-triggered rockfalls to provide means to assess relative probabilities of rockfall generation in future earthquakes. This criteria is based upon rock-mass fracture characteristics that can be rapidly assessed and plotted allowing rockfall susceptibility of large areas to be evaluated and statistically compared.

Instrumentation Sites

Two sites, one in the San Francisco Bay area and one in the greater Los Angeles area have been instrumented to collect strong-motion, displacement, and pore-pressure data from active landslides likely to be reactivated in a future earthquake. Surface accelerometers have been installed both on and off the landslide masses, pore-pressure transducers (piezometers) within the slide masses below the water table, and extensometers across headwall scarps and lateral shear surfaces of the slides. During future earthquakes, surface accelerations, pore-water pressures, and displacements will be recorded simultaneously. The successful recording of such data will greatly enhance the understanding of the physics of the interaction between seismic inertial forces and the landslide-triggering and movement process.

A site in the Santa Cruz Range near La Honda, California has been instrumented to record future earthquake effects on a landslide within the San Francisco Bay area. The landslide selected was one that showed slight displacement (0.5 cm) along its lateral shear surfaces in response to the Loma Prieta earthquake. In southern California, a site at Chantry Flat north of Santa Anita Canyon on a deep-seated landslide mass that was reactivated (~ 15 cm displacement in its lower midsection) in the 1991 Sierra Madre earthquake has been instrumented. The site at Chantry Flat has been instrumented with three accelerometers, one on the landslide reactivated during the 1991 Sierra Madre earthquake, one on the ancient surrounding landslide mass, and one on stable bedrock. Two extensometers have been deployed across the 1991 scarp. Bedrock conditions at the site precluded installation of piezometers and inclinometer casing with existing in-house drilling capabilities.

The La Honda site has been instrumented with two surface accelerometers, one on the slide mass and one adjacent to it on stable ground, four piezometers at various depths, and two extensometers, all to be recorded simultaneously after being triggered by a seismic event. The piezometers and displacement meters are also recorded on a long term basis to provide displacement and pore-pressure data prior to an earthquake and for several hours or days after shaking stops.

Liquefaction

Historic data from worldwide earthquakes was studied to determine if a magnitude-epicentral distance relation could be found for the occurrence of liquefaction effects. Distances from earthquake epicenters to the farthest documented sites of liquefaction were compiled for historic worldwide data that had previously been used to establish magnitude-distance relations for landslides on steep slopes.

International Earthquakes

Reconnaissance of the area affected by the July 12, 1993, Hokkaido-Nansei-Oki earthquake (M 7.8) in Japan was conducted as part of a combined EERI-UJNR team to
investigate the earthquake and its effects. Landslide reconnaissance was conducted on Okushiri Island and on the southern peninsula of Hokkaido.

Paleoseismicity

More than 200 landslides in the New Madrid seismic zone have been analyzed from several perspectives. Most recently, we analyzed the results of detailed geological and geotechnical site investigations of two representative landslides to determine the likely conditions leading to failure.

Loma Prieta Earthquake

Reports were finalized for inclusion in a multi-article professional paper chapter on landslides and stream-channel changes caused by the earthquake.

Results:

Shaking Tresholds For Landslides

Comparison of Arias-intensity values calculated from strong-motion records from the 1987 Whittier Narrows and Superstition Hills earthquakes in southern California with landslide limits for these two earthquakes yields threshold ranges of 0.08-0.6 m/s for Tertiary and younger deposits and 0.01-0.07 m/s for Mesozoic and older rocks. These two thresholds appear to be influenced mainly by geologic site conditions, specifically the degree of fracturing and aperture (“openness”) of the rock or soil mass. The lower threshold is found in rock masses that have been intensely fractured and have apertures of 10-20 cm commonplace as well as having loose rock present on existing slopes.

A comparison of Arias intensities with landslides occurrence for the 1989 Loma Prieta earthquake is still in progress.

The August 14, 1988, M_L 5.3 earthquake in Emery County, Utah, and the April 29, 1993, M_L 5.3 Western Arizona earthquake, centered near Delle, Arizona, triggered rock falls at 129 km and 169 km respectively from the earthquake epicenters. This is compared to previous historic limits for rock falls of 29 km for M 5.3 earthquakes. The September 2, 1992, St. George, Utah, earthquake of M_S 5.6 triggered a rotational slump/block slide of 14 million m^3 volume near Springdale, Utah, at the west entrance of Zion National Park. The epicentral distance to this landslide is 44 km and greatly exceeds the previously known epicentral distance of 18 km for this type of landslide. The exceedance of these distance limits within the Colorado Plateau suggests that there may be a significant difference in the attenuation characteristics of seismic energy within this region. Because most of the historic earthquake data from which epicentral distance limits have been previously derived has come from earthquakes near plate margins, we suspect that a gap exists in the worldwide data gathered so far and that distance limits for landslides away from plate margins may be significantly greater than those previously documented.

Found the source of the seismic signals recorded on the Lassen National Park seismic network on 29 August 1993 that lasted 3 1/2 minutes. The source of these signals was a rock fall/rock slide of approximately 10,000 m^3 that occurred at a notch 700 m ENE of the summit of Mt. Lassen at an elevation of 2,900 m. Investigation confirmed volume estimate made by U.S.G.S. seismology branch in Seattle on the basis of the duration and amplitude of the seismic signal recorded.
Investigation of the landslides triggered by the September 20, 1993, Klamath Falls, Oregon, earthquake sequence (largest event M 6.0) established that most of the slope failures caused by this sequence were rock falls, rock slides, and slumps within artificial fill, typical for most moderate earthquakes. Also confirmed that epicentral distance limits relative to the largest event for landslides were well within established historic limits for earthquakes worldwide.

Rockfall Susceptibility

Reports on regional and site-specific criteria have been recently published. These criteria provide methods to assess and evaluate the seismic rockfall potential on a regional basis (for example, within a county) and on a site specific basis (for example, within rock cliffs next to a potential development site or along a highway right-of-way). These criteria will give engineers and planners useful tools with which to assess seismic rockfall hazard and to make development and zoning decisions.

Instrumentation Sites

Sites have been instrumented in both the San Francisco Bay area and in southern California close to active faults likely to generate at least a magnitude 5-6 earthquake within the next ten years. The equipment was installed during summer 1992 and upgraded to measure long-term background data as well as that generated during an earthquake. The accelerometers at Chantry Flat in southern California were triggered by the Landers, California, earthquake of June 28, 1992 and have all produced records. Ground motion at Chantry Flat during this earthquake was not sufficiently large to produce measurable displacements within the instrumented landslide mass.

Liquefaction

Magnitude-distance relations established for liquefaction effects from worldwide earthquake data indicate that the attenuation of seismic shaking necessary to cause liquefaction is independent of region. The data suggest that, regardless of whether an earthquake occurs near a plate margin or continental interior, earthquakes of equivalent magnitude will trigger liquefaction effects at comparable distances if susceptible deposits exist in both regions. A corollary of this finding is that magnitudes of historic earthquakes where instruments were not present to record a magnitude, can be estimated using distances of liquefaction effects.

International Earthquakes

The July 12, 1993, Hokkaido-Nansei-Oki earthquake (M 7.8) triggered landslides throughout Okushiri Island as well as throughout much of the southwestern Hokkaido peninsula. The slides consisted mainly of rock falls and rock slides on steep (>50°) natural and engineered cut slopes. Volumes ranged from several cubic meters to the 800,000 m$^3$ rock slide that buried the Yo Yo Hotel at Okushiri Port. Numerous slumps also occurred in engineered fill along highways and railways.
Paleoseismicity

We have developed an approach for determining if old landslides of unknown origin were more likely to have formed seismically or aseismically. A static stability analysis of aseismic conditions is conducted to determine if failure could have occurred under any reasonable set of conditions, such as ground-water fluctuations. If aseismic failure can be reasonably ruled out, a dynamic analysis using Newmark's sliding-block method is conducted to determine the minimum shaking conditions required to cause the observed failure. Such analyses can thus ascertain if a landslide was seismically triggered and, if so, the likely shaking conditions leading to failure. We also developed a general empirical relationship between landslide displacement, earthquake shaking intensity, and the dynamic stability of a landslide, as measured by its critical acceleration. This relationship is applicable in paleoseismic studies: if an old landslide can be shown to have been seismically triggered, and if the landslide movement can be dated, the date and shaking intensity of the triggering earthquake can be estimated. This approach also has application in seismic hazard analysis: the performance of slopes of known stability can be estimated under a postulated set of shaking conditions.

Loma Prieta Earthquake

Articles for a multi-article professional paper chapter documenting and interpreting landslides and other coseismic features from the earthquake are in press.

Reports Published:


Harp, Edwin L., and Jibson, Randall W., (in review), Seismic instrumentation of landslides: Building a better model of dynamic landslide behavior, (technical note to be submitted to BSSA), 20 ms. p.


Jibson, R.W., Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis: Transportation Research Record [accepted].
Liquefaction Research

3-9960-12286

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Program Element III

Investigations

The liquefaction research project undertook multiple investigations in FY93 including:

1. Completion of the compilation of field occurrences of liquefaction during the 1989 Loma Prieta earthquake.
2. A field deployment of portable seismographs to improve ground motion estimates at sites that experienced liquefaction during the 1989 Loma Prieta earthquake. The goal of the deployment is to permit rigorous testing of the simplified procedure for predicting liquefaction with geotechnical data collected following Loma Prieta.
3. Compilation and analysis of geotechnical data collected by the USGS at 1989 liquefaction sites in the Monterey Bay area.
4. A field study that identified a new mechanism for generating sand boils and liquefaction features by nonseismic means.
5. An evaluation of the fidelity of pore-pressure transducer response at the Wildlife, California, liquefaction array.
6. Cooperative agreement with the Applied Technology Council to transfer USGS results from engineering seismology research to the practicing design engineer (ATC-35).
Results

1. Documentation and compilation of the field occurrences of liquefaction during the 1989 Loma Prieta earthquake were completed. Locations of 133 occurrences of liquefaction were compiled on maps at a 1:100,000 scale and associated effects were described in a detailed table (Tinsley and others, in press). Damaging liquefaction was observed to a distance of 84 km from the end of the seismic source zone which is greater than that observed in most earthquakes.

2. Portable digital seismographs were deployed at seven sites beginning in August 1993 to improve our estimates of ground motion during the Loma Prieta earthquake at sites that experienced liquefaction. The August 11, 1993, Hall’s Valley M4.9 earthquake was recorded at several of the sites and the recordings permit an evaluation of localized variations in site response (Fig. 1). The two records shown in Figure 1 were for sites that were 0.76 km apart, but were located on Holocene floodplain alluvium of different ages. The upper record was obtained on young Holocene floodplain alluvium and the lower record was obtained on old Holocene floodplain alluvium. Extensive liquefaction including lateral spreading occurred in the former but only isolated sand boils occurred in the latter. The spectral ratios of the two records suggest that amplification of higher frequency ground motion has occurred at the site on younger Holocene floodplain alluvium.

3. A total of 150 cone penetration tests and 334 standard penetration tests in 58 borings have now been conducted at 18 sites, 14 of which displayed liquefaction-related ground failure in the Monterey Bay area. Index properties of soils sampled in the areas of ground failure have been determined for comparison with soil properties in areas where ground failure did not occur. Supporting soils data and penetration test data have been entered into a geotechnical database using GTGS® software. We now have a good suite of basic soils engineering data to conduct analyses of the ground failures that we have studied in detail. Analyses of the 2-km-long lateral spread south of Watsonville indicate liquefaction occurred over a 5-m-thick interval of sand in the younger floodplain facies. The top of layer was 5 m from the land surface. Observed settlements and lateral spreading displacements agree with those predicted by standard engineering methods.

4. Preservation in the stratigraphic record of sedimentary deformation that was caused by earthquake-induced liquefaction has become a useful means for inferring the occurrence of prehistoric strong earthquakes in areas that lack evidence of surface faulting. We undertook a field study of sand boils in Fremont Valley, California, that formed in the absence of earthquake shaking. We concluded that field evidence similar to that from earthquake-induced liquefaction can be produced when sediment-laden surface runoff is intercepted by and reemerges from preexisting ground cracks. The investigation reinforces the importance of excluding nonseismic mechanisms for paleo liquefaction features observed in the field that are used to infer prehistoric strong earthquakes (Holzer and Clark, 1993).

5. In response to an urgent need for field data from instrumented sites, the U.S. Geological
Survey selected and instrumented a site in 1982 in southern California called the Wildlife site. The site experienced liquefaction in the 1987 Superstition Hills earthquake and the instrumentation yielded the first recording of earthquake-induced liquefaction under field conditions. Because of a long time delay in the build up of pore pressure to overburden pressure, the fidelity of the records has been challenged. We reviewed the response of the transducers and subsequent analyses of site response and concluded that the acceleration recordings are consistent with the delayed increase of pore pressure and that the records may provide the first quantitative measure of ground oscillation during liquefaction (Youd and Holzer, 1994).

6. Planning was completed for the seminar *New developments in earthquake ground motion estimation and implications to engineering design practice* which is to be held in January-February 1994 in Los Angeles, Memphis, New York, San Francisco, and Seattle.

See report by Tinsley, this volume, for additional information concerning USGS liquefaction research.

**Reports**


Fig. 1. Comparison of ground motions recorded near Watsonville at site on younger Holocene floodplain alluvium with site on older Holocene floodplain alluvium during the August 11, 1993, Hall's Valley earthquake. Sites are 0.76 km apart. Spectral ratios of upper record to lower record are shown in lower graph.
Severe ground failure occurred in the unconsolidated sediment during the New Madrid earthquakes of 1811 and 1812. An eyewitness’s account as quoted in Fuller (1912) says that “the earth rolled in waves several feet high with visible depressions between the swells, finally bursting and leaving parallel fissures for distances as great as 5 miles in some cases.” These ground rolls are most likely surface waves. Recently, the magnitude 4.6 Risco, MO, earthquake of May 5, 1991 generated surface waves lasting more than 3 minutes (Dorman and Smalley, 1993). In addition to surface waves, resonant amplification of body waves trapped in the sediment can cause damage to structures at shorter periods. A rational evaluation of earthquake hazard in the Mississippi Embayment requires knowledge of the structure of the Embayment as well as physical properties of the sediment and their underlying Paleozoic rocks. Perhaps the most important physical property needed for hazards evaluation is shear-wave velocity profile of near-surface sediment because these velocities can account for a significant part of the large surface-wave amplitude and body-wave amplification. The aim of this project is to measure detailed shear-wave velocity profile of sediments in the New Madrid Seismic Zone; shear-wave attenuation measurements will also be attempted.

Results

1. In consultation with Professor J. Dorman of the Center for Earthquake Research and Information (CERI) of Memphis State University and Dr. S. Horton of Lamont-Doherty Earth Observatory (LDEO) of Columbia University, three sites: Shelby Forest, Tennessee (located on loess deposits where the Mississippi River has never meandered); Marked Tree, Arkansas (located on the Mississippi flood plain); and Risco, Missouri (also located on the Mississippi flood plain) are selected for downhole \( V_s \)-measurement. A strong-motion-accelerometer network is maintained in the New Madrid Seismic Zone jointly by CIRE and LDEO.

2. A hole is drilled to a depth of 192 ft and cased with 4-inch Schedule 40 PVC pipe at the Shelby Forest, Tennessee site. 18 standard penetration tests (SPT) were conducted
during the drilling. In addition to the split-spoon samples obtained from the SPT tests, 11 relatively undisturbed Shelby-tube samples were also obtained. Stratigraphy at the site consists of 38 1/2 ft of loess underlain by layers of clay and clayey-silty sand with seams of lignitic sand; a layer of sandy clay mixed with gravel extends from 56-ft depth to 65 1/2-ft depth.

3. A hole is drilled to a depth of 122 ft and cased with 4-inch Schedule 40 PVC pipe at the Marked Tree, Arkansas site. The stratigraphy consists essentially of two sand layers. The upper layer 3-30 ft and the lower layer 30-122 ft differ from one another by the degree of compaction and the amount of lignitic fragments; the lower layer was more compacted and contains more abundant lignitic fragments. The top 3 feet of soil consists of clayey silt. 16 SPT tests were carried out during the drilling operation. The drill hole caved in at 122-ft depth where a clean gravel bed was encountered. The present site differs markedly from the Shelby Forest, Tennessee site in that both sands and gravels contain negligible amount of fines, reflecting active ground-water seepage in the Mississippi flood plain.

4. A hole is drilled to a depth of 93 ft and cased with 4-inch Schedule 40 PVC pipe at the Risco, Missouri site. The stratigraphy consists essentially of two sand layers. The upper layer 3-59 ft and the lower layer 59-93 ft both contain abundant lignite fragments but differ from one another by the degree of compaction; the lower layer was more compacted. The top 3 feet of soil consists of clayey silt. 15 SPT tests were conducted during the drilling operation. The drill hole caved in at 93-ft depth where a clean gravel bed was encountered. Similarly to the Marked Tree, Arkansas site, both sands and gravels contain negligible amount of fines, reflecting active ground-water seepage in the Mississippi flood plain.

5. A borehole shear-wave generator using the same principle as that of a surface shear-wave generator (Liu et al., 1988) has been designed and construction has begun at U.S.G.S. A wireline borehole intensifier which generates 1,500 psi hydraulic pressure from a 12-volt DC source and a hydraulic borehole wall lock have been completed. The hammer unit, which impacts the wall lock to generate the shear waves, is expected to be completed in FY 1994.

6. Results of in-situ shear-wave absorption measurement in the San Francisco Young Bay Mud have been summarized in a manuscript submitted to the Bulletin of the Seismological Society of America.

7. A three-component borehole seismometer has been installed in Pleistocene bay clay (Old Bay Mud) at 30-m depth in the Marina District of San Francisco, completing a three-level vertical seismic array with seismometers at the surface, in the Old Bay Mud, and in the bedrock. Seismograms from bay-area earthquakes recorded by this array will be used to assess the effects of the Old Bay Mud (Pleistocene clay) and the Young Bay Mud (Holocene clay) in amplifying ground motions at the surface.

8. Outreach activities: participation in a National Science Foundation workshop on Geophysical Techniques for Site and Material Characterization held in Atlanta, Georgia in June of 1993; tutoring high school students in Academic Decathlon at Palo Alto High
School in Palo Alto, California.

Reference cited


Reports

Laboratory experiments are being carried out to study the physical properties of rocks at elevated confining pressure, pore pressure and temperature. The goal is to obtain data that will help us to determine what causes earthquakes and how to predict them. The relevant investigations cover a broad range of conditions. Stick-slip instabilities, which are the laboratory counterpart to earthquakes, are studied to understand both the dynamics of rupture and the processes leading to fault instability. Additional studies of permeability and chemical reactions that can occur in the crust at seismogenic depths are conducted to understand the large crustal system that loads earthquake-prone faults. Investigations are also underway to study conditions of borehole stability to aid in the interpretation of field data related to crustal stress measurements.

Results

Frictional Properties of Rocks

Increasing evidence that the San Andreas fault has low shear strength has fuelled considerable discussion regarding the role of fluid pressure in controlling fault strength. Byerlee [1990, 1992] and Rice [1992] have shown how fluid pressure gradients within a fault zone can produce a fault with low strength while avoiding hydraulic fracture of the surrounding rock due to excessive fluid pressure. It may not be widely realized, however, that the same analysis shows that even in the absence of fluids, the presence of a relatively soft ‘gouge’ layer surrounded by harder country rock can also reduce the

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1 M. Blanpied and S. Hickman, U.S. Geological Survey, Menlo Park, California; D. Scott and C. Sammis, University of Southern California, Los Angeles, California; L. Vernik, Stanford University, Stanford, California; M. Rusanov, Nedra Enterprise, Yaroslavl, Russia; T. Röckel, KTB Oberfalz, Windisch-eschenbach, Germany; L. Liu, Institute of Geology, State Seismological Bureau, Beijing, China; B. Armstrong, formerly I.B.M., Palo Alto, California.
effective shear strength of the fault. As shown most recently by *Byerlee and Savage* [1992], as the shear stress across a fault increases, the stress state within the fault zone evolves to a limiting condition in which the maximum shear stress within the fault zone is parallel to the fault, which then slips with a lower apparent coefficient of friction than the same material unconstrained by the fault. Here we confirm the importance of fault geometry in determining the apparent weakness of fault zones, by showing that the apparent friction on a sawcut granite surface can be predicted from the friction measured in intact rock, given only the geometrical constraints introduced by the fault surfaces. This link between the sliding friction of faults and the internal friction of intact rock suggests a new approach to understanding the microphysical processes that underlie friction in brittle materials.

In a related study, triaxial compression experiments were performed on samples of natural granular fault gouge from the Lopez fault in southern California. This material consists primarily of quartz and has a self-similar grain size distribution thought to result from natural cataclasis. The experiments were performed at a constant mean effective stress of 150 MPa, to expose the volumetric strains associated with shear failure. The failure strength is parameterized by the coefficient of internal friction, $\mu$, based on the Mohr-Coulomb failure criterion.

Samples of remoulded Lopez gouge have internal friction $\mu = 0.6 \pm 0.02$. In experiments where the ends of the sample are constrained to remain axially aligned, suppressing strain localization, the sample compacts before failure and dilates persistently after failure. In experiments where one end of the sample is free to move laterally the strain localizes to a single oblique fault at around the point failure; some dilation occurs but does not persist. A comparison of these experiments suggests that dilation is confined to the region of shear localization in a sample. Overconsolidated samples have slightly larger failure strengths than normally consolidated samples, and smaller axial strains are required to cause failure. A large amount of dilation occurs after failure in heavily overconsolidated samples, suggesting that dilation is occurring throughout the sample. Undisturbed samples of Lopez gouge, cored from the outcrop, have internal friction in the range $\mu = 0.4-0.6$; the upper end of this range corresponds to the value established for remoulded Lopez gouge. Some kind of natural heterogeneity within the undisturbed samples is probably responsible for their low, variable strength. In samples of simulated gouge, with a more uniform grain size, active cataclasis during axial loading leads to large amount of compaction. Larger axial strains are required to cause failure in simulated gouge, but the failure strength is similar to that of natural Lopez gouge. Use of the Mohr-Coulomb failure criterion to interpret the results from this study, and other recent studies on intact rock and granular gouge, leads to values of $\mu$ that depend on the loading configuration and the intact or granular state of the sample.

*Connections Between Rate-Dependence of Strength of Intact Rock and Gouge*

The coefficient of friction of a Coulomb material is expressed as $\mu = \tau (\sigma - \sigma_t) = \tan \phi$ where $\tau$ and $\sigma$ are shear and normal stress, $\sigma_t$ is tensile strength and $\phi$ is the friction angle. *Byerlee and Savage* [1992] showed that an idealized fault system composed of a Coulomb material (gouge) sheared between parallel rigid fault surfaces will evolve to a condition...
in which the apparent coefficient of friction $\mu_a$, determined from the remotely applied stresses, is given by $\mu_a = \sin \phi$. Thus a mature fault described by the Byerlee-Savage model will always appear weaker than the true frictional strength controlling the micro-mechanical deformation within the gouge layer (e.g., $\sin \phi < \tan \phi$ for realistic values of $\phi$). Lockner and Byerlee [1993] recently pointed out a connection between internal friction $\mu_i$ of intact granite and $\mu_a$ for sliding friction on fault surfaces. They reasoned that the same processes of grain crushing and crack growth are responsible for damage accumulation in intact rock and for deformation in a fault zone. They showed that by equating the true micro-mechanical friction within a gouge zone with internal friction for intact granite, the apparent fault friction $\mu_a$ could be predicted from the simple relation

$$\mu_a = \sin(\tan^{-1} \mu_i).$$  

We now present further evidence to support this notion by using (1) to relate strain-rate-dependence on intact rock strength to rate dependence of $\mu_a$ in triaxial friction experiments. We have conducted triaxial creep and fracture experiments on intact samples of Westerly granite to determine $\partial \mu_i / \partial \dot{\varepsilon}$. This rate sensitivity successfully predicts the instantaneous slip-rate-sensitivity $a = \partial \mu_a / \partial \ln V$ as used in the Dieterich-Ruina frictional constitutive law. Inelastic brittle deformation of granite and sandstone has been identified with subcritical microcrack growth. The rate dependence of tensile subcritical crack growth in quartz has also been shown to satisfactorily explain the rate dependence of stress in compressive creep tests. Thus, our current analysis supports the hypothesis that the instantaneous rate sensitivity of friction in brittle rock is the result of subcritical crack growth at grain contacts.

**Effects of Fluids on Fault Strength and Stability**

We have conducted triaxial measurements demonstrating that shear-rate-dependent dilatancy observed in dry fault gouge has a strong stabilizing influence when the gouge is saturated and hydraulically isolated from its surroundings. In this case, a pore volume increase results in lowered pore pressure and therefore increased effective normal stress and shear strength. When applied to crustal faults, this effect would suppress rupture nucleation in favor of slow creep. In one experiment, we sheared a 1-mm-thick layer of quartz gouge in an undrained condition at a nominal pore pressure of 50 MPa and confining pressure of 100 MPa. Slip rate cycling between 0.01 and 10 $\mu$m/s resulted in an apparent rate-dependent frictional variation of 0.060 (i.e., $(a - b) \approx +0.009$). This value is 2 to 10 times greater than (and opposite in sign to) typical rate-weakening values reported for dry bare-rock surfaces. A second experiment in which a drillhole allowed direct communication of pore fluid between the fault gouge and the external system showed essentially zero slip-rate dependence and measurable rate-dependent pore volume variations similar to those reported by Morrow and Byerlee (1989), Marone et al. (1990) and Marone and Kilgore (1993). From our observations we infer that fault zone fluid pressure dropped 14% in our first experiment, resulting in an increase in effective normal stress and the observed increase in shear strength.
If large crustal strike-slip faults are weak due to entrapment of pore fluid at superhydrostatic pressure, this same rate-dependent dilatancy mechanism could be expected to operate. In this case, dilatancy-strengthening effects acting through an increase in effective pressure are expected to more than offset rate-weakening effects reported for bare dry rocks. Laboratory measurements of gouge-filled faults, which would seem a better analog for crustal fault systems than bare rock, generally report neutral to rate-strengthening friction. Thus it would appear that a model based solely on rate-dependent friction would be insufficient, by itself, to result in an earthquake triggering mechanism.

It has been proposed that large strike-slip faults contain water in seal-bounded compartments. Heat flow and other energy budget arguments suggest that in most of the compartments the water pressure is so high that the average shear strength of the fault is less than 10 MPa. We propose a variation of the model in which most of the shear stress on the fault is supported by compartments where the pore pressure is relatively low. As a result, the material in the fault zone is compacted and lithified and its undisturbed strength is high. When one of these locked sections fails, the system made up of the nearby high and low pressure compartments can become unstable. The material in the high pressure compartments is initially underconsolidated since consolidation is retarded by the low effective confining pressure. When slip occurs the underconsolidated material in the shear zone will compact, pore pressure will increase and the fault in these zones will become weaker (similar to observations by Blanpied et al. (1992) in laboratory experiments). In the low pressure compartments, the material is initially overconsolidated and when slip occurs it will dilate and reduce pore pressure. However, it can be shown that in this case the increase in strength due to the increase in effective stress is more than offset by the decrease in strength due to displacement-weakening of the fault (i.e., the drop from peak to residual strength). If the surrounding rock mass is sufficiently compliant to produce an instability, slip will propagate along the fault until the shear fracture runs into a low-stress region, even if dilation causes the pore pressure in the initially overconsolidated regions to decrease from hydrostatic to zero during the dynamic event.

Permeability Resistivity and Acoustic Properties of Core Samples from Deep Drillholes.

Permeability measurements were conducted on intact core samples from the Kola drillhole in Russia and the KTB drillhole in Germany. Samples included granodiorite gneisses, basalts and amphibolites from depths up to 11 km. The tests were intended to determine the pressure sensitivity of permeability, and to compare the effects of stress-relief and thermal microcracking on the matrix permeability of different rock types and similar samples from different depths. Pore pressure, $P_p$, was fixed at the estimated in situ pressure assuming a normal hydrostatic gradient; confining pressure, $P_c$, was varied to produce effective pressures ($P_e = P_c - P_p$) of 5 to 300 MPa. The permeability of the basaltic samples was the lowest and most sensitive to pressure, ranging from $10^{-20}$ to $10^{-23}$ m$^2$ as effective pressure increased from 5 to only 60 MPa. In contrast, the granodiorite gneiss samples were more permeable and less sensitive to pressure, with permeability values ranging from $10^{-17}$ to $10^{-22}$ m$^2$ as effective pressures increased to 300 MPa. Amphibolites displayed intermediate behavior. There was an abundance of microfractures in the quartz-rich rocks, but a relative paucity of cracks in the mafic rocks suggesting that the observed differences
in permeability are based on rock type and depth, and that stress-relief/thermal-cracking damage is correlated with quartz content. By applying the equivalent channel model of Walsh and Brace [1984] to the permeability data of the quartz-rich samples, we can estimate the closure pressure of the stress-relief cracks and thereby place bounds on the \textit{in situ} effective pressure. This method may be useful for drillholes where the fluid pressure is not well constrained, such as at the Kola well. However, the use of crack closure to estimate \textit{in situ} pressure was not appropriate for the basalt and amphibolite samples, because they are relatively crack-free \textit{in situ}, and remain so even after core retrieval. As a result, their permeability is near or below the measurable lower limit at the estimated \textit{in situ} pressures of the rocks.

We measured P-wave velocity, two orthogonally polarized S-wave velocities and relative attenuation on 12 cores recovered from the Kola superdeep well at depths of 0 to 12 km. Measurements were made along the core axis at a frequency of 1 MHz, at confining pressures ranging from 2 to 100 MPa, and under dry and water-saturated conditions. Samples were chosen to sample a variety of lithologies and these data were used to estimate interval velocities using a simplified geological column of the well. These interval velocities were then compared with sonic log and vertical seismic profile (VSP) data. High-pressure velocities correlated primarily with rock composition and texture. These lab velocities are generally in good agreement with both sonic log and VSP data, suggesting that extremely low velocities as measured in unconfined samples or at low confining pressure are the result of drilling and core-recovery-induced damage. The magnitude of this microcrack-induced damage increases progressively with depth in a step-wise manner, but with a few notable inversions. These inversions are characterized by a relatively small reduction in dry unconfined velocity compared to the in-situ velocities. We interpret these inversions to be due to localized in-situ stress relief related to faulting, fracturing and/or hydrothermal alteration. We also observed pronounced S-wave splitting in these cores, the analysis of which suggests that these stress-relief microcracks tend to be aligned parallel to the foliation in gneisses and amphibolites (dip angle 30°–45°) rather than being subhorizontal. These observations have important implications for the nature of gently dipping seismic reflections detected in the immediate vicinity of the Kola well.

**Permeability Loss in Rock at Geothermal Conditions**

Recent studies of active and exhumed faults have demonstrated the importance of fluid-rock interactions to fault-zone processes at depth. Successful modeling of these processes will require knowledge of the permeability of rock and gouge materials at elevated temperatures and pressures. To this end, we are measuring the permeability of Westerly granite under hydrothermal conditions. Experiments to date have been conducted at a confining pressure of 150 MPa and a pore pressure of 100 MPa, using deionized water as the pore fluid. The samples are cylinders 21.9 mm long and 19.1 mm in diameter. In repeated experiments at 500°C, intact granite cylinders showed initially uniform rates of permeability decrease of 9–15% per day, from starting values of 3.5 to $4.5 \times 10^{-19}$ m$^2$. After 4 to 5 days, however, permeability dropped rapidly (in less than a day) to values on the order of $10^{-22}$ m$^2$. We are also conducting permeability experiments using a layer of ultrafine granite gouge sandwiched between intact rock cylinders. Solubility rates as well
as total solubilities are higher for ultrafine-grained particles than for coarse-grained pieces of a given mineral or rock type. Therefore, we expect to observe enhanced permeability reduction rates driven by precipitation from supersaturated fluids expelled by the ultrafine-grained gouge layer. SEM investigations are being conducted to identify the mechanisms of permeability loss. Permeability reduction is being modeled using percolation theory, in which the stage of rapid decrease in flow rate occurs as the percolation threshold is approached.

**Internal Geometry of Fault Systems**

The geometry of recently active breaks in the San Andreas fault system has been investigated to explain the occurrence of fault creep in central California. Fault-trace orientations within segments of the locked and creeping sections were found to differ in two ways: (1) P-type subsidiary traces are more abundant than R-type traces in the creeping sections, whereas R traces predominate in the locked sections; (2) The maximum angle that R traces make to the local fault strike is smaller in the creeping sections than in the locked sections. These distinguishing characteristics can be explained by comparison to laboratory friction experiments on simulated gouge. Offset along an echelon array of R traces results in shortening across the fault zone, whereas offset on a P array results in dilation. Most laboratory faults are sheared at relatively high effective stresses, and in those samples R traces are better developed than P traces. However, if an experiment is conducted at a low enough normal stress that dilation is possible, the P traces will predominate over the R traces. R-trace angles are smaller in stably sliding laboratory gouge layers than in ones that show stick-slip motion; any conditions promoting stable slip, including low stresses, will favor small R-trace angles. The geometric characteristics of the creeping sections thus are consistent with stable slip, but their origin is open to question. Velocity and gravity studies indicate that the fault zone is wider in the creeping sections than in the locked sections. Mapping by Rymer (1981) suggests that, at least locally, this wide zone is produced by diapirc upwelling of a serpentine-rich mass. One possible explanation for the geometry of the creeping zones is that near-lithostatic fluid pressure and correspondingly low effective stresses are maintained in this wide zone of low-permeability material. High fluid pressures have been postulated for the San Andreas system as a whole, but a range of high fluid pressures could exist such that only in the creeping sections do they exceed some critical level that allows preferential formation of P traces. Differences in fluid pressure between the locked and creeping sections could be confined to the upper few kilometers of the fault zone; if so, the observed fault geometry would only be representative of near-surface conditions. Alternatively, the numerous P-traces might reflect continued serpentine diapirism at depth.

**Microcrack Populations as Indicators of Stress Intensity Around a Propagating Shear Fracture**

Microcracking related to the formation of a laboratory shear fracture in a cylinder of Westerly granite has been investigated using image-analysis computer techniques. Granite located well away from the fracture (far field) in the deformed sample has about twice the crack density (crack length per unit area) of undeformed granite. The microcrack
density increases dramatically in a process zone that surrounds the fracture tip, and the fracture tip itself has more than an order of magnitude increase in crack density over the undeformed rock. Microcrack densities are consistently higher on the dilational side of the shear than on the compressional side. Microcracks in the undeformed rock and in the far-field areas of the laboratory sample are concentrated within and along the margins of quartz crystals, but near the shear fracture they are somewhat more abundant in K-feldspar crystals. The microcracks that formed during the experiment are principally tensile cracks whose orientations reflect the local stress field: those formed prior to the initiation of the fault are roughly parallel to the cylinder axis (loading direction), whereas those generated in the process zone make angles averaging 30–40° to the overall fault strike (and 20–30° to the cylinder axis). The preferred orientation and uneven distribution of microcracks in the process zone suggest that the process zone has an asymmetrical shape about the fracture tip. The microcrack fabric in the process zone provides an easy propagation path for the shear, even though the trend is away from the overall fault strike. As a result, the propagating shear follows the microcrack trend for some distance and then changes direction in order to maintain an overall in-plane propagation path. This recurring process produces a zig-zag or sawtooth segmentation pattern similar to the sawtooth geometries of faults such as the San Andreas.

**High Frequency Acoustic Emission Monitoring Near Parkfield, California**

An array of four high frequency transducers (30 kHz resonance) has been deployed in shallow holes adjacent to the Varian well near Parkfield, Ca to monitor naturally occurring acoustic emissions. We will attempt to relate these signals to tidal strains, creep events and strains associated with nearby earthquakes. A recent experiment at the San Francisco Presidio [Valdes-Gonzalez et al., 1992] demonstrated that naturally occurring AE were generated in response to both diurnal thermoelastic heating and earth tides. Correlation of the AE signals with nearby strain measurements indicated that the AE is sensitive to local strains on the order of $10^{-9}$. Thus, AE monitoring (in the 10 to 60 kHz range) may be of potential use as a local strain monitoring device. Since the acoustic signals in this frequency range suffer rapid attenuation, devices of this type must be responding to strains within a few tens of meters of the transducer. We have now deployed our shallow transducer array and are in the process of solving noise and instrumentation problems associated with the high gain needed in this system. Once the system is operational, we will conduct continuous monitoring of local acoustic emission noise and attempt to relate the observed event rates to earth tides, creep events and nearby earthquakes. The successful correlation of AE with earth tides is considered the most important objective since this will provide a measure of the sensitivity of AE to local strain changes.

**Articles and Papers:**


Abstracts:


EVALUATION OF THE NEWMARK METHOD
FOR MAPPING EARTHQUAKE-INDUCED LANDSLIDE
HAZARDS IN THE LAUREL 7.5' QUADRANGLE,
SANTA CRUZ COUNTY, CALIFORNIA

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Award 1434-93-G-2334
Program Element III3

INVESTIGATION

The purpose of this project is to evaluate the applicability of the Newmark dynamic slope stability method to regional hazard mapping by comparing hazard maps prepared by the method with mapped ground failures caused by the 1989 Loma Prieta earthquake. The Newmark method, with some variations, has been utilized for regional hazard mapping in San Mateo County and the City of Oakland, California (Wieczorek, et al., 1985; Legg, et al., 1982), and in Davis and Salt Lake Counties, Utah (Keaton, et al., 1987). Unfortunately, no significant earthquake has yet occurred in these areas which would allow for the evaluation of the Newmark method as a predictor of seismically-induced slope failures.

This project is a pilot study for the Division of Mines and Geology's Seismic Hazard Evaluation and Zoning Project, and it is anticipated that many of the methodologies developed in this study will be used to zone seismic slope stability hazards throughout the California. To facilitate the production of hazard zone maps, the Division is implementing a Geologic Geographic Information System (G-GIS). Therefore, this project is also looking at ways to manipulate digital geologic, geomorphic and geotechnical information in a GIS environment to maximize the speed and accuracy of regional hazard mapping.

Two models are simultaneously being developed to test the applicability of the Newmark method in the Laurel quadrangle in the Southern Santa Cruz Mountains. The first model is the "predictive model", which is the model developed by the USGS and applied in San Mateo County (Wieczorek, et al, 1985). The second model is the "comparative model", a compilation of mapped Loma Prieta ground failures combined with a detailed landslide inventory for the Laurel quadrangle. This model will be used to test the validity of the predictive model.

At least two predictive susceptibility maps will be generated. The first will be prepared using a nearly identical procedure as the San Mateo County seismic slope stability map. Geologic materials have been grouped into three strength categories, and percent slope categories have been derived from a 1975 slope map prepared by the U.S. Geological Survey.
using photogrammetric methods. Subsequent predictive maps will use information more appropriate to a 1:24,000 scale analysis. This includes the use of a 1:24,000 scale digital geologic map, strength data from laboratory-derived testing and back-analysis, and slope data derived from a 7-meter resolution DEM.

RESULTS

Comparative Model

The compilation of Loma Prieta earthquake ground failures is complete. Data were collected from both published and unpublished sources (see references). This compilation will be digitized into a GIS file and compared with the landslide inventory to separate out earthquake landslide features from ridge-top spreading features.

First Predictive Map Generation

This phase of the project is rapidly approaching completion. An unpublished digital geologic map of the Laurel quad was obtained and successfully translated from the U.S. Geological Survey's Branch of Western Regional Geology (Wentworth, 1993). The 1975 slope map has been separated into overlays of different slope categories, and these are now being digitized for computer manipulation. The landslide inventory for this analysis will consist of the landslides shown on the geologic map. Because many of the geologic formations in the Laurel quad are also found in San Mateo County, we will use the same susceptibility matrix as used in the preparation of the San Mateo County seismic slope stability map (Wieczorek, et al., 1985).

Second Predictive Map Generation

The second generation of susceptibility maps will follow the same general procedure as the first, but will incorporate more detailed data. Geotechnical boring log and laboratory strength test data, as well as surface and subsurface geologic site investigation data, were collected from reports on file with the Santa Cruz County Planning Department. The geotechnical laboratory strength test data have been compiled into a computer data base and statistically evaluated for as many geologic formations as possible. Out of the 35 mapped geologic formations and units within the Laurel quadrangle, lab test data were available for 19 of them. The geologic materials that have strength data include the most aerially extensive formations in the study area. Where possible, the strength data for each mapped formation were divided into three strength categories: 1) median peak values of all material types for intact rock with favorable bedding conditions; 2) median peak values of only finer-grained materials for intact rock with adverse bedding conditions; and 3) median residual strength values for existing landslide areas. In a few selected cases, strength parameters will be calculated for significant recent landslides and the results compared with the strength data collected from geotechnical reports. Geologic materials for which there are no data will be grouped with geologically similar formations which have data.
A landslide inventory based largely on older photography is being generated. This inventory will be more complete than that shown on the geologic map, and more reliable than the existing inventory (Cooper-Clark and Associates, 1974). The photos being emphasized in this study were taken in 1931, 1939 and 1943. Much of the Santa Cruz Mountains was logged in the late 1800's and early 1900's, and these early air photos provide a relatively unobscured view of the ground surface allowing landslide recognition more reliable.

GIS-Related Accomplishments

Beyond the typical and often tedious task of digitizing data into a GIS system, there have been several accomplishments in particular which will have a significant impact on future hazard mapping. The first is the use of the Division's image processing workstation and "soft copy" photogrammetry to generate stereo models from old, non-calibrated aerial photography. Because these stereo models are rectified to a coordinate plane and have an apparent spatial accuracy of 50 feet or better, landslide features can be digitized directly from the stereo image and made into a GIS map layer. It is now possible to avoid the standard practice of inking features on air photo overlays, transferring them to a map via zoom transferscope, and digitizing the results into the GIS.

An important goal of using GIS information is the effective assimilation and distribution of data among the users of that information. We have been successful in translating an unpublished digital geologic map for the Laurel quadrangle from a USGS ARC/INFO GIS file. The necessary steps and file formats required for future data exchanges with the Survey have now been established. In addition, we have requested a parcel map in an Auto CAD format from the Santa Cruz County Planning Department. The parcel map will assist in digitizing mapped Loma Prieta Earthquake ground failures and will establish the procedures for data transfer between the Division and the County.

Finally we have ordered, received and translated USGS Digital Line Graphs (DLG) and a 7-meter resolution Digital Elevation Model (DEM) for the Laurel quadrangle. The DLG's will be used mostly for display purposes and limited analyses, while the DEM data will be used for preparation of slope maps for the second predictive model maps.

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SOURCES OF LOMA PRIETA EARTHQUAKE GROUND FAILURE INFORMATION

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Scaling of Seismic Sources

9930-10433

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Element III

Investigations

1. Seismic data recorded locally, both on the surface and underground are analyzed to gain insight into the seismic source process, especially with regard to source scaling.

2. A special issue of Pure and Applied Geophysics entitled "Induced Seismicity" is in preparation.

3. Source processes of crustal earthquakes are analyzed in terms of applied forces and crustal rheology.

Results

1. The analysis of ground motion of mining-induced tremors in deep south Africa gold mines reveals two distinct types of moment tensors. The first type is a double-couple mechanism (generally assumed for tectonic earthquakes) involving slip across normal faults. The second entails normal faulting plus a comparable amount of implosive deformation. Interestingly, for a given moment or magnitude, the double-couple events produce substantially higher levels of high-frequency, potentially damaging ground motion than do those with a significant implosive component.

2. The special issue of PAGEOPH "Induced Seismicity" was published late in 1993.

3. A comparison of stick-slip friction in a large, granite laboratory sample with mining induced earthquakes in South Africa and Canada has stimulated a working hypothesis to the effect that seismic efficiencies have an upper bound of about 0.06. This hypothesis is exciting in that, if confirmed, then measurements of seismically radiated energy could be used to map out absolute levels of deviatoric stress in the crust. A report describing these results is currently in the review process.
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INVESTIGATIONS UNDERTAKEN

Liquefaction occurred at numerous sites in the San Francisco Bay Region during the 1989 Loma Prieta earthquake. At many urban sites, liquefaction caused considerable damage to infrastructure and lifeline facilities.

Research investigations in this project are focused on the characterization and prediction of two aspects of liquefaction response: post-liquefaction consolidation and ground oscillation. Post-liquefaction consolidation occurs as excess pore water pressure is dissipated in granular soil, resulting in densification and settlement of the liquefied layer. Ground oscillation is defined as the large-amplitude transient deformation of liquefied deposits during ground shaking. Both types of deformation may cause severe damage to facilities built on or within potentially liquefiable deposits. The City of San Francisco sustained 169 breaks in its network of municipal water mains, primarily at locations of liquefaction-induced ground deformation. A major fire developed in the Marina District after the 1989 earthquake, due in part to loss of water pressure from broken water mains. The fires following the 1906 and 1989 earthquakes in San Francisco attest to the importance of liquefaction as an urban seismic hazard with immense potential for damage.

Compilation of Case Studies

Case studies of liquefaction associated with the Loma Prieta earthquake were compiled, with emphasis given to quantitative observations of settlements and lateral movements at near level sites. Optical survey data and field measurements of differential settlements next to pile-supported structures were obtained to provide information regarding post-liquefaction consolidation. Information was gathered on pavement cracking and buckling, inclinometer profiles, and seismograph records. Where possible, detailed records of stratigraphy and in-situ soil density, such as provided by cone penetration tests, were obtained.

Most sites for which measurements were obtained consist of uncompacted, dumped or hydraulically placed fills near San Francisco. Figure 1 illustrates the location of sites reviewed in the central Bay Area, including the Mission, South of Market, Foot of Market, North Beach, and Marina Districts of San Francisco; Treasure Island, Port of Richmond,
Port of Oakland 7th Street Terminal, and Alameda Naval Air Station. Measurements also were obtained at Moss Landing and the City of Santa Cruz in the Monterey Bay area, which are underlain by loose to medium dense alluvial and beach sands.

Level Surveys

Municipal surveys in San Francisco and Santa Cruz before the Loma Prieta earthquake provide a baseline for evaluation of liquefaction settlements. Post-earthquake surveys, including information provided by city agencies and from published data, were supplemented by optical level surveys by project researchers during March 1993. The research team performed over 10 km of optical leveling in the Mission, South of Market, Foot of Market, and Marina Districts of San Francisco that tie into pre-earthquake
benchmarks. Resurvey of multiple benchmarks at most intersections increased the level of confidence in the survey results and allowed for patterns of differential settlement to be evaluated.

RESULTS OBTAINED

Development of Predictive Methodology

Both case studies and laboratory observations suggest that liquefaction-induced ground deformation is correlated strongly with site geometry, and in particular, with the thickness of the liquefiable layer. Previous research indicates that the magnitude of settlement caused by post-liquefaction consolidation in the Loma Prieta earthquake (Pease, et al., 1992) and the magnitude of horizontal displacement associated with lateral spreads in the 1906 San Francisco earthquake (Pease and O’Rourke, 1993) and several Japanese earthquakes (Hamada, 1992a and 1992b) are proportional to the thickness of liquefiable deposits.

A promising methodology for prediction of post-liquefaction consolidation settlement has been proposed by Ishihara and Yoshimine (1992). This method uses laboratory results that show vertical strain is controlled by the maximum shear strain, which can be related to the in-situ density and factor of safety against liquefaction. Both density and factor of safety can be evaluated from in-situ penetration test data. A computer program is being developed presently as part of this research to implement and simplify computation of settlement strain and shear strain using cone penetration test (CPT) results.

Figure 2 illustrates a typical analysis, using cone penetration test data obtained in the Marina District. Figure 2a indicates the CPT tip resistance and a soil profile interpreted from adjacent conventional borings and soil correlations with CPT. The thickness of potentially liquefiable, saturated soils is determined on the basis of soil type. The factor of safety in Figure 2b is determined for the predicted peak acceleration and earthquake magnitude with methods such as those proposed by Seed and deAlba (1986) and Mitchell and Tseng (1992). Using the relationships proposed by Ishihara and Yoshimine (1992), Figure 2c illustrates the vertical strain of the deposit, which when integrated over each element of depth, provides a prediction of settlement at the ground surface. Similarly, shear strains can be predicted which provide an estimate of the amplitude of ground oscillation.

HAZARD MAPS

There is a remarkable spatial correlation between locations of thickest liquefiable fills in San Francisco and areas of most severe damage in the 1906 and 1989 earthquakes. On the basis of these observations, hazard maps have been developed for several locations, such as for the South of Market and Mission areas of San Francisco, as illustrated in Figures 3 and 4 (Pease and O’Rourke, 1993).

In Figures 3 and 4, shaded areas which denote regions with greater than 2 m of liquefiable soils are associated with high levels of lateral displacement in the 1906
earthquake. Other liquefaction features, including subsidence, sand boils, ground deformations, and pavement offsets, are likely to be found in proportion to the severity of lateral deformation, and therefore also are related to liquefiable thickness. For example, in Figure 3 the highest concentration of damage after the Loma Prieta earthquake in the South of Market was observed on 7th Street between Mission and Folsom Streets, on 6th Street near Bluxome Street, and near U.S. 101 on Brannan Street.

The zones with potential for significant liquefaction-induced ground movement are indicated by the hatchured areas in the maps. Potentially liquefiable zones on the hatchured side of the upper bound contour include areas where the base of fill occurs within 2 m above mapped groundwater levels to areas with as much as 6-8 m of submerged loose fill. The upper bound contour encompasses the region of uncertain saturation of fill due to fluctuations in groundwater levels and variation in fill thickness, and appears to bound the historic occurrence of damage. The limits of liquefaction in the Mission District (Figure 4) roughly agree with the delineation of liquefaction zones in previous studies. In contrast, the upper bound for liquefaction in the South of Market in Figure 3 is drawn recognizing the presence of deep fills in dune depressions which were not acknowledged in previous works.

Pease and O'Rourke (1993) identify other factors which influence the potential for liquefaction in the areas of submerged fill deposits. A dashed contour indicates regions where the thickness of non-liquefiable surface soils \( (H_{\text{f}}) \) is greater than 3 m. Areas where greater than 3 m of unsaturated fill overlie liquefied deposits did not show evidence of liquefaction after the 1989 Loma Prieta earthquake. More than 80% and 50% of submerged fills in Figures 3 and 4, respectively, are comprised of clean, poorly graded
Figure 3. Liquefaction Hazard Map of the South of Market, San Francisco, California

Figure 4. Liquefaction Hazard Map of the Mission District, San Francisco, California
sand. While the direction of lateral spread in these areas was consistent in the direction of the maximum surface slope, neither the magnitude of ground deformation nor the severity of buried pipeline damage was found to correlate well with surface slope. For the City of San Francisco, therefore, the thickness of potentially liquefiable deposits provides the most effective index for estimating the areal extent of severe liquefaction effects. This type of index can be adapted readily to Geographical Information Systems (GIS) and provides a powerful tool for assessing earthquake effects in design and planning studies.

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9920-10022

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(303) 273-8850

Investigations and Results

The Quick Epicenter Determination (QED) continues to be available to individuals and groups having access to a 300- or 1200-band terminal with dial-up capabilities to a toll-free WATS number or a commercial telephone number in Golden, Colorado. It is also accessible via GEONET and public TYMNET. The QED has become one of our most popular ways of making near-real-time earthquake information available to the general public and scientists throughout the world. The time period of data available in the QED is approximately three weeks (from about two days behind real time to the current PDE in production). The QED program is available on a 24-hour basis, 7 days a week. From October 1, 1992 through September 30, 1993, there were 64,000 logins to the On-Line Information System, which includes the QED, earthquake lists, and a geomagnetic field values program to generate QED programs. A daily QED message, 7 days behind real time, is transmitted to many different agencies in the United States and throughout the world via electronic mail, including a scientific bulletin board operated by Dr. Francis Wu at the State University of New York at Binghamton. This bulletin board is accessible by anyone who is connected to BITNET. The daily QED message is also distributed to another 32 agencies via U.S. government communications (VADATS/DTS/AUTODIN), including worldwide distribution on the communications system of the World Meteorological Organization.

NEIS is making extensive use of electronic mail for data acquisition. Data are now being received via GEONET, TYMNET, internet, BITnet, DECNET/SPAN and uucp on a regular basis from several dozen agencies. Some of the agencies sending data to the NEIS via electronic mail included the following:

- Universidad Autonoma de Mexico, Mexico City
- Istituto Nazionale di Geofisica, Rome, Italy
- Centre Seismologique Euro-Mediterranean, Strasbourg, France
- Kandilli Observatory, Istanbul, Turkey
- Harvard University, Cambridge, MA (Centroid, Moment Tensor Solutions)
- Graefenberg Observatory, Germany
- Icelandic Meteorological Institute, Reykjavik, Iceland
In addition, the following agencies contribute data to the PDE program by computer file transfer or remove login via the computer networks:

<table>
<thead>
<tr>
<th>Agency</th>
<th>Location</th>
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<tbody>
<tr>
<td>USGS Calnet and Alaska Seismic Projects</td>
<td>Menlo Park</td>
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<td>USGS/California Institute of Technology</td>
<td>Pasadena</td>
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<tr>
<td>USGS Fredericksburg Observatory</td>
<td>Corbin, Virginia</td>
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<tr>
<td>University of California, Berkeley</td>
<td></td>
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<tr>
<td>University of Southern California</td>
<td>Los Angeles</td>
</tr>
<tr>
<td>University of Washington</td>
<td>Seattle</td>
</tr>
<tr>
<td>Oklahoma Geophysical Observatory</td>
<td>Leonard</td>
</tr>
</tbody>
</table>

The following organizations are now receiving the automatically located earthquakes from the NSN system when an earthquake is located for specified magnitudes:

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Event Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. Smriglio, ING, Rome, Italy</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>S. Sipkin, USGS/NEIC</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>J. Fyen, NORSAR, Norway</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>Inst. of Geophysics, UNAM, Mexico</td>
<td>&gt;=4.8 in/near Mexico</td>
</tr>
<tr>
<td>T. Heaton, CalTech, Pasadena</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>Duty Officer, PTWC, Honolulu</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>U. Kradolfer, ETH, Zurich, Switz.</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>USGS CalNet Duty Officer, Menlo</td>
<td>&gt;=4.0 in CA or NV</td>
</tr>
<tr>
<td>Japan Meteorological Agency, Tokyo</td>
<td>&gt;=5.5 worldwide</td>
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<tr>
<td>Union Pacific Railroad, Omaha NE</td>
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</tr>
<tr>
<td>T. Ahern, IRIS/DMC, Seattle</td>
<td>&gt;=5.5 worldwide</td>
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<tr>
<td>B. Hammond, AEIC, Fairbanks</td>
<td>&gt;=2.5 in AK</td>
</tr>
<tr>
<td>Duty Officer, CSEM, Strasbourg, France</td>
<td>&gt;=5.5 worldwide</td>
</tr>
<tr>
<td>Duty Officer, ReNass, Strasbourg, France</td>
<td>&gt;=5.5 worldwide</td>
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<tr>
<td>S. Malone, Univ. of Washington</td>
<td>&gt;=2.5 in WA or OR</td>
</tr>
</tbody>
</table>
Recipient | Event Criteria
--- | ---
M. Villagran, INSIVUMEH, Guatemala | \( \geq 4.8 \) in/near Guatemala
J. Mendoza, FUNVISIS, Venezuela | \( \geq 5.0 \) in/near Venezuela
E. Norabuena, IGP, Lima, Peru | \( \geq 5.5 \) in/near Peru
FEMA, Washington, DC | \( \geq 4.5 \) in contig. US, HI, or central or SE AK
D. Rosen, UN Radio Readiness Group, NY | \( \geq 5.5 \) worldwide
Duty Officer, IGN, Madrid, Spain | \( \geq 5.5 \) in/near Spain
USGS Calnet Computer, Menlo Park | \( \geq 2.5 \) in CA or NV
or | \( \geq 4.5 \) in contig. US
or | \( \geq 5.5 \) worldwide

Telegraphic data are now being exchanged with the Russia on most larger earthquakes. The data from the countries of the former Soviet Union are being received from the Central Seismological Observatory, Obninsk, under the auspices of the World Data Center system. Our designation as World Data Center A for Seismology played a key role in permitting this exchange to be established.

Data from the People’s Republic of China via the American Embassy continue to be received in a very timely manner and in time for the PDE publication. We continue to receive four stations on a weekly basis from the State Seismological Bureau of the People’s Republic of China. The Bulletins with additional data are now being received by floppy disk in time for the Monthly. We are in the process of establishing routine data exchange by electronic mail.

Special efforts are being made to receive more data from the Latin American countries on a more timely basis. The increased availability of telefax and electronic mail is permitting much more interaction with Latin American countries than in the past, but there are still problems getting data on timely basis for many large earthquakes.

We have rapid data exchange (alarm quakes) with Centre Seismologique Euro-Mediterranean (CSEM), Strasbourg, France and Istituto Nazionale de Geofisica, Rome, Italy, and Sicily, and data by telephone from Mundaring Geophysical Observatory, Mundaring, Western Australia and Pacific Tsunami Warning Center in Honolulu. The geophysical laboratory in Papeete, French Polynesia contributes a single-station estimate of seismic moment within about 24 hours of a large event in the Pacific region. We also have the capability to dial into computers at the Australian Geological Survey Organization, Canberra, Australia, and Swiss Seismic Services at Zurich, Switzerland, and collect data on recent earthquakes. The Monthly Listing of Earthquakes is up to date. As of September 30, 1993, the Monthly Listing and Earthquake Data Report (EDR) have been completed through May 1993. The total number of events located for 1992 was 19,548, an increase of 3,032 from 1991, the largest number for any given year. Radiated energy, moment tensor, P-wave first-motion and broadband depth solutions continue to be determined by the
USGS when possible and published in the Monthly Listing and EDR for any earthquake having an $m_b$ magnitude $\geq 5.8$. Moment tensor solutions are being computed by the NEIC, and centroid, moment tensor solutions contributed by Harvard University are being published in the Monthly Listing and EDR. Moment tensor solution and broadband depth are being published in the QED for selected events. Also, the $M_w$ magnitude is being published on a routine basis in the QED, PDE, and Monthly Listing for most earthquakes of magnitude 5.5 and above.

The Earthquake Early Alerting Service (EEAS) continues to provide information on recent earthquakes on a 24-hour basis to the Office of Earthquakes, Volcanoes, and Engineering; scientists; news media; other government agencies; foreign countries; and the general public.

One-hundred and forty-two releases were made from October 1, 1992 through September 30, 1993. The most significant earthquakes in the United States were as follows:

- On November 27, 1992, a magnitude 5.4 in southern California. Slight damage occurred in the Big Bear area.
- On March 25, 1993, a magnitude 5.5 at the Washington-Oregon border. Numerous people were treated for minor injuries. Damage (VII) was reported at Canby, Molalla, Mount Angel, and Newberg, Oregon. Slight damage was reported in other parts of Oregon.
- On May 11, a magnitude 2.8 in Pennsylvania, near Reading. One person in Reading area lost his balance because of the earthquake, fell off his bicycle, and was injured. This is believed to be one of the smallest earthquakes in the U.S. for which confirmed casualty report have been received.
- On May 13, a magnitude 6.8 on the Alaska Peninsula. There were reports of items being knocked from shelves at San Point and King Cove.
- On May 15, a magnitude 6.6 earthquake occurred in the Andreanof Islands, Aleutian Islands. It was felt strongly on Adak.
- On September 21, a magnitude 5.8 in southern Oregon. One person was killed by an earthquake-induced landslide along highway 97, north of Klamath Falls. Another person died of a heart attack.
- On September 21, a magnitude 5.7 in southern Oregon, causing additional damage.
- On August 7, a magnitude 6.5 in the Gulf of Alaska. There were no reports of damage.
- On September 2, a magnitude 5.8 in Utah. Damage at Springdale, Hurricane, and New Harmony, as well as landslides in the Springdale area.
- On September 30, a magnitude 6.6 in the Andreanof Islands, Aleutian Islands. There were no reports of damage.
The most significant foreign earthquakes were as follows:

**Egypt**
- On October 12, 1992, a magnitude 5.9. At least 2,541 people were killed, and more than 6,500 people were injured. The earthquake destroyed at least 8,300 buildings in the Cairo area. Preliminary estimates of damage were about 300 million U.S. dollars.

**Colombia**
- On October 17, 1992, a magnitude 7.0 in northern Colombia. At least 20 people were injured and about 90 percent of the buildings were destroyed in Murindo.
- On October 18, 1992, a magnitude 7.3 in northern Colombia. One person was killed, 50 were injured, and damage was reported in the Murindo-Apartado-Medellin area. In addition, at least 10 people were killed, 65 were injured, and 1,500 were left homeless by the explosion of a mud volcano in the San Pedro de Uraba area.

**Egypt**
- On October 22, 1992, a magnitude 4.5 aftershock. At least four people were killed, and 50 people were injured in the Cairo area.

**Morocco**
- On October 23, 1992, a magnitude 5.2. At least two people were killed in Rissani.

**Eastern Caucasus**
- On October 23, 1992, a magnitude 6.5. At least one person was killed, 10 were injured, and several houses were damaged in the Barisakho-Georgia area. Landslides were reported in the epicentral area.

**Switzerland**
- On November 2, 1992, a magnitude 4.5 explosion. Six people were killed from the accidental explosion at an ammunitions cavern.

**Indonesia**
- On December 12, 1992, a magnitude 7.5 in the Flores Region. This was the most damaging earthquake of 1992. At least 2,200 people were killed or were reported missing in the Flores region, including 1,490 people at Maumere and 700 on Babi. More than 500 people were injured, and 40,000 people were left homeless. Nineteen people were killed and 130 houses were destroyed on Kaloatoa. Severe damage was reported at Moumene, where 90 percent of the buildings were destroyed by the earthquake and tsunami. Fifty to eighty percent of the structures on Flores were damaged or destroyed. Damage also occurred on Sumba and Alor. Tsunami run-up of 300 meters with wave heights of 25 meters was reported on Flores. There were reports of landslides and ground cracks at several locations around the island.

**Japan**
- On January 15, 1993, a magnitude 7.1 in the Hokkaido region. Two people were killed, 614 people were injured, and substantial damage was reported at Kushiro.
- On July 12, 1993, a magnitude 7.6 in Hokkaido region. At least 200 people were killed, and 39 people were reported missing in the Hokkaido region, including at least 165 people killed on Okushiri. Extensive damage was caused along the southwestern coast of Hokkaido from the earthquake and the tsunami.
Mariana Islands
- On August 8, 1993, a magnitude 8.1 south of the Mariana Islands. Forty-eight people were injured on Guam. Extensive damage occurred to hotels in the Tumon Bay area. Damage was reported to facilities at the commercial port and naval base at Apra Harbor.

India
- On September 29, 1993, a magnitude 6.3 in southern India. May be as many as 30,000 people were killed (9,748 people were confirmed killed), 30,000 people were injured, and extreme devastation occurred in the Latur-Osmanabad area.

Reports


Monthly Listing of Earthquakes and Earthquake Data Reports (EDR); 12 publications from June 1992 through June 1993. Compilers: Jacobs, W., Chang, P., Koyanagi, S., Lavonne, C., Minsch, J., Needham, R., Person, W., Presgrave, B., Schmieder, W.


Preliminary Determination of Epicenters (PDE); 52 weekly publications from October 5, 1992 through September 24, 1993, numbers 36-91 through 35-93. Compilers: Jacobs, W., Chang, P., Minsch, J., Person, W., Presgrave, B., Schmieder, W.


Significant Earthquakes of the World (October 1, 1992 - September 30, 1993)
Analysis of Structural Response to Earthquakes

9920–10282

Erdal Safak
Branch of Earthquake and Geomagnetic Information
U.S. Geological Survey
922 National Center
12201 Sunrise Valley Drive
Reston, Virginia 22092
(703) 648–6908

Investigations

The investigation involves analyzing site amplification in layered media by using the discrete-time wave propagation techniques. Although the wave propagation in layered media is a well-studied subject and a large number of references are already available in the literature, almost all of the previous investigations have considered the problem in the frequency domain. The discrete-time domain approach to the problem is more natural, since all the recordings are in discrete time. Compared to the more popular frequency-domain techniques, the discrete-time approach is much simpler and provides a better physical insight to the problem.

In the investigation, we formulate the wave propagation by using the discrete-time state-space formulation, where the upgoing and downgoing waves in the layers are considered as the state variables. The damping due to solid friction (i.e., Q-damping) in the soil is included in the formulation by converting the frequency domain attenuation expression into a discrete-time recursive filter. The formulation results in simple discrete-time filters that can be used to calculate the transfer functions for site amplification, and to simulate soil-site motions for given rock-site motions and site characteristics.

Results

The discrete-time formulation of the wave propagation results in simple analytical models for site amplification. When compared to the previous ones, these new models have the following important advantages: (1) they use the physical parameters of the site, including the damping due to solid friction (i.e., Q-attenuation; (2) for a single soil layer over bedrock subjected to vertically propagating waves, the model is exact and uses only three parameters; (3) not only the amplitudes, but also the phase characteristics of the site are accounted for in the models; (4) the models can incorporate the multiple reflections of waves in the layer; and (5) the models result in simple time-domain recursive filters for simulating ground motions.
The models introduced in this study also provide convenient tools to develop random vibration models, to generate site specific response spectra, and to identify site characteristics from recorded motions.

Reports


Safak, E., 1994, Modeling effects of surface geology on ground motions: To be presented at the 10th European Conference on Earthquake Engineering, Vienna, Austria, August 28–September 2, 1994 (invited paper).

Estimates of Ground Motion Amplification and Duration in Saint Louis, Missouri, Metropolitan Area Due to New Madrid Earthquakes

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566 El Dorado Street, Pasadena, CA 91101

Introduction: For the design seismic safety guidelines for various lifelines and geotechnical works, it is necessary to understand the influence of local geologic and site conditions in the urbanized area on the incoming ground motions from large earthquakes occurring in a potentially active fault zone. Central United States (CUS) is one such region which consists of several seismic zones, each capable of causing large earthquakes. The ground shaking, fault rupture, landslide, and liquefaction during and after such large earthquakes may cause serious damages to different lifelines in the area (FEMA, 1991).

Objectives: In this study, we want to investigate the level of ground motions in the greater Saint Louis area, Missouri, especially the level of long-period ground motions in Saint Louis due to three large New Madrid earthquakes, magnitude ranging from $M_w=6.5$ to $7.5$. The final goal of this study is to make estimates of peak acceleration, spectral values, duration and time-histories including the long-period information. The time histories will be used to investigate site specific one-dimension equivalent linear response analysis.

Research Accomplishments: We have completed simulation of long-period seismograms at several sites in Saint Louis using fault models designed previously by Saikia (1992) for three earthquakes, magnitude ($M_w$) ranging from $6.5$ to $7.5$, occurring in New Madrid seismic zone. The fault dimensions are based on constant stress-drop model developed for the eastern North America (Somerville and others, 1987). Saikia (1992) simulated high-frequency seismograms using the semi-empirical method (Somerville and others, 1991), showing that the peak ground motions from the constant and the increasing stress-drop models are not significantly different in this magnitude range.

To simulate the long-period seismograms at Saint Louis, we computed a set of 56 broadband Green’s functions at distances ranging from 240 to 350 km for 17 depths, in the range of 0.6 km to 14.76 km. Figure 1 shows the crustal model used in this study. The crust is slightly inelastic ($Q_a=1000$ and $Q_p=500$ across the entire crust). Notice that the model does not include the sedimentary layer. The rationale is that only the waves from the source region diving downward would arrive at Saint Louis due to the source-receiver geometry. The path effects computed for the shallowest depth is dominated by the long-period surface waves and those for the deepest source mostly by the body waves. Depending on where slip is concentrated on the fault surface, the seismograms at Saint Louis may be dominated either by surface waves or body waves. We used randomly generated 15 slip models to investigate the level of both the peak ground motions and the spectral values. Figure 2 shows some of these slip models for $M_w=7.5$. These models were generated using a model for the wavenumber spectrum of the slip on the fault using seismic moment, fault dimension, depth of maximum slip and two-dimensional Fourier phase and amplitude spectrum of the slip distribution on the fault. The wavenumber
The spectrum derived from the analysis of the wavenumber spectra of western North American earthquakes is the basis for the model of Fourier phase and amplitude spectrum of the New Madrid earthquakes. The randomness in the phase spectrum decreases with the spatial increase in the wavelength. Generally, the phase spectrum affects the location of the asperities, and the degree of correlation between phase in the along strike and down-dip directions affects the shape of the asperities. The models are tapered so that the variation of slip with depth is preserved and possibility of large slip at the end of the fault is avoided.

**Methodology:** The approach to simulate long-period seismograms is that of Hartzell and Heaton (1983). In this investigation, we have a forward problem and simulate ground motions with appropriate time delay due to the rupture front for individual fault elements using the interpolation scheme to predict propagation effect from the coarsely computed Green’s functions as used by Hartzell and Heaton (1983). However, since the City of Saint Louis is several hundred kilometers away from the source, the interpolation is based on the travel times predicted by analytical curves obtained by fitting selected phases (say, $S^1$, $S^2$, $S^3$, $S^4$) as shown in Figure 3. Thus, for the same phase, the analytical curves have different representation at individual depths. The final time history at Saint Louis is predicted by multiplying the simulated seismograms of each fault, say of the $i$-th fault, with the weighted seismic moment ($M^W_i$), and summing them, where

$$M^W_i = M^P_i G$$

$$M^P_i = \mu_i A_i D_i N^i M_o^P$$

and

$$G = M_0 \sum_{i=1}^{n} M^P_i$$

where $\mu_i$, $A_i$, $D_i$, and $N^i$ are the rigidity, area, slip displacement, number of sub-sources used to generate the seismogram of the $i$-th fault and $M^P_i$ is the seismic moment used (generally $1.0 \times 10^{20}$ dyne-cm) in generating the Green’s functions. $M_o$ is the target seismic moment in dyne-cm.

**Results:** Figure 4 shows a set of synthetic seismograms simulated for the various slip models for $M_w=7.5$ earthquake. The slip time function is an idealized one defined by a triangle whose duration is specified following the relation presented by Somerville and Abrahamson (1991). In addition to the waveshapes, the level of the peak ground motion appear to vary depending upon the chosen slip model. Figure 5 shows similar long-period waveforms at Saint Louis for $M_w=7.0$ earthquake. The corresponding slip models are presented in Figure 6.

**References**


Figure 1. Crustal Model for CUS Unit in Km/s

Figure 2. Slip Models

New Madrid Earthquake Mw=7.5
Slip Model: 1
Slip Contours
New Madrid Earthquake Mw=7.5

Slip Model: 2

Slip Model: 3

Slip Model: 4

Figure 2 (Contd).
Figure 3

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<tr>
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<tr>
<td>2</td>
<td>3.60km/s</td>
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<td>4</td>
<td>3.25km/s</td>
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Long-Period Seismograms at Saint Louis for New Madrid Earthquake $M_w=7.5$

Slip Model - 1

Slip Model - 2

Slip Model - 3

Slip Model - 4

Figure 4
Long-Period Seismograms at Saint Louis for New Madrid Earthquake Mw=7.0

Slip Model - 1

Slip Model - 2

Slip Model - 3

Slip Model - 4

Figure 5
New Madrid Earthquake $M_w=7.0$

Slip Model : 1

Slip Contours

Slip Model : 2

Slip Contours

Slip Model : 3

Slip Contours

FIGURE 6
Objective: Predict low-frequency (0.1-0.6 Hz) site amplification in East Salt Lake Basin by 2-D and 3-D elastic wave-propagation modeling. The East Salt Lake Basin model is obtained by a 3-D gravity inversion with constraints from CDP seismic profiles (McNeil, 1991). The East Salt Lake Basin model in Figure 1 (71 km by 107 km by 5 km in the east-west, north-south and depth directions) consists of a semi-consolidated layer surrounded by bedrock, and the synthetic seismograms are obtained by 4th-order staggered grid finite-difference solutions to the 2-D and 3-D elastic wave equation (see Table 1).

Results: A 3-D elastic-wave simulation is carried out for a P-wave propagating vertically from below, where the source bandwidth of the Ricker wavelet is from 0.1 Hz to 0.6 Hz. Figure 2 shows maps of the peak particle velocity ratios and the accumulated kinetic energy ratios in the East Great Salt Lake Basin. These maps suggest that the largest amplification generally occurs in the vicinity of sites located above the deepest parts of the basin. This result is consistent with the results of 2-D simulations by Hill et al. (1990) and Murphy (1989), and the 3-D simulations by Olsen et al. (1991).

The locations of sites associated with the largest values of peak particle velocity ratios and accumulated kinetic energy ratios (Figure 3) show the influence of the three-dimensional deep structure in basin amplification. The largest values of the ground motion parameters are generally not associated with sites located immediately above the deepest points of the basin; they are found at sites nearby where the gradient of the basin slope is large. This is in agreement with the results of Olsen et al. (1991). The maximum values of peak particle velocity ratios and accumulated kinetic energy ratios are listed in Table 2.

Ongoing and Future Work: Recent results from 3-D modeling in the Salt Lake Basin (Olsen et al., 1993) suggest that the shallow sedimentary layers (thickness of about 100-300 meters) influence the site amplification as much as the deep layers. Our current/future simulations will include these near-surface layers into the basin model. We will also simulate horizontally propagating SH- and Rayleigh wave sources, and account for some attenuation effects.
References


841
<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
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<td>Temporal Discretization (s)</td>
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<td>P-wave velocity in sediments (km/s)</td>
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Table 1: 3-D modeling parameters

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<tr>
<td>N-S PEAK PARTICLE VELOCITY</td>
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<tr>
<td>V PEAK PARTICLE VELOCITY</td>
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<td>V ACCUMULATED KINETIC ENERGY</td>
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</table>

Table 2: Maximum values of peak particle velocity and accumulated kinetic energy in the East Great Salt Lake Basin on the E-W, N-S and vertical components for a simulation with a vertically incident plane P wave. The values in the table are normalized by those simulated at a rock site.
Figure 1. Depth to bedrock model of East Salt Lake Basin obtained from 3-D gravity inversion (McNeil, 1991). Contour interval is 1000 m.
Figure 2  Maps of peak particle velocity ratios and accumulated kinetic energy ratios in the East Great Salt Lake Basin on the E-W, N-S and vertical component seismograms for a simulation with a vertically incident plane P wave. The values calculated for the vertical component at a rock site are used as reference. Contours shorter than approximately 16 km are considered beyond the resolution of the model and have been discarded from the plot. The contour map at the bottom shows the depth to the bedrock interface at 1000 m contour interval; the shallowest contour at 320 m is superimposed on the ground motion plots (thick line) for reference. The simulation parameters are listed in Table 1.
Figure 3  Location of sites associated with the largest values of peak particle velocities (P) and accumulated kinetic energies (E) on the E-W, N-S and vertical (V) components. The contours depict the depth to the bedrock interface at 1000 m interval (shallowest contour at 320 m).
In Southern California, working in collaboration with Ruth Harris and David Castillo, we have begun the construction of a dislocation model that will contain the important active tectonic elements in the region. This model will be used after future large earthquakes to identify, in near real-time, the locations of structures that have become more loaded (hence more dangerous) as a result of the static stress changes after the earthquake. We have also begun investigations of the 1857 Ft. Tejon ($M_{8+}$) earthquake on the San Andreas fault and the 1952 Kern County ($M_{7.2}$) earthquake to see if spatial and temporal patterns in seismicity after these large shocks are consistent with changes in the static stress field.

In Northern California, working with Kate Breckenridge, Jon Galehouse, Jim Lienkaemper, and Paul Reasenberg, we continue to study the creep rate and microseismicity rate changes on the San Andreas, Calaveras, and Hayward faults caused by the 1989 Loma Prieta earthquake. We have made simple models of these faults in an effort to explain the rate changes.

Results

**Southern California:** Working with Ruth Harris, we published a study of the stress changes on the San Andreas fault caused by the 1992 Landers earthquake. The results suggest that stresses loaded onto parts of the San Bernardino segment could advance the onset of the next large earthquake on that segment by 10-20 years. Stresses were relaxed on the Mojave segment of the San Andreas, which seems to be consistent with microseismicity rate changes reported by Hauksson and others. We also contributed a stress change section to the SCEC Phase I report on the Landers earthquake, and contributed static stress change calculations to the paper by Hill and others on triggered seismicity after Landers.
We are finding that, with a few exceptions, the earthquakes that occurred in the 50 years after the 1857 Ft. Tejon earthquake seem to fall into regions where the Coulomb failure stress increased, while the regions in which the Coulomb failure stress decreased do not have moderate or large earthquakes until after 1907. David Castillo examined a number of scenarios for triggering of 1952 aftershocks by the mainshock. Working with old earthquakes is rather frustrating because the residual uncertainties regarding locations, magnitudes, and focal mechanisms force one to deal with multiple scenarios. It appears that the ambiguities in the 1952 slip distribution allow for the possibility of static stress changes contributing to triggering of the aftershocks. There also appears to be a decrease in the number of small earthquakes in the Transverse Ranges after 1952 that may be consistent with calculated decreases in Coulomb failure stress, if these small events are assumed to have a thrust component to their mechanisms.

Northern California: The acceleration of creep rates on the San Andreas fault south of the 1989 rupture is slowly dissipating exponentially with time, but rates have still not returned to background levels. Creep rates on the Calaveras and southern Hayward faults which were slowed or reversed after 1989 are still below long-term background rates. Models suggest that the slowdown could last until 1995 or even 1999 on some fault segments. We hope that by monitoring the nature and timing of the return to normal rates, we will learn something about how these major faults are responding to static stress changes and something about the rheology of the fault zones. Models of the San Andreas fault under the five creepmeters that were accelerated after 1989 suggest that these meters are responding to anomalous creep rates that extended to depths of at least 10 km and that a near-surface response alone cannot explain the amounts of excess slip. Slower rates at Cienega Winery creepmeter in the 2-3 years before Loma Prieta may reflect local adjustments in the triangle between the San Andreas and Calaveras faults after the 1986 Tres Pinos earthquake. These local adjustments and the 1986 earthquake itself could possibly be the result of regional tectonic adjustments that eventually triggered the Loma Prieta earthquake, although the mechanism for such triggering is not clear.

Reports


INVESTIGATIONS

Ground motion conditions that are of little concern for conventional structures can be quite important for structures having natural periods longer than 1 second. For example, a large long-period pulse of motion, due to the effect of rupture propagation (directivity), is observed in the direction normal to the fault at strong motion stations located close to the fault. The fault-normal motions are about twice as large as the fault-parallel motions for periods longer than about 1 second. The "time compression" effect of rupture directivity which is partly responsible for the large amplitude also causes the motion to arrive at the beginning of the record and to have a relatively brief duration compared with that experienced at other locations.

The conditions required for the generation of this pulse are met when the direction of the SH radiation pattern maximum in the slip direction and the direction of rupture propagation coincide. These conditions are readily met in strike-slip faulting. A maximum in the SH radiation pattern is oriented in the direction along strike, and rupture propagates along strike either unilaterally or bilaterally. All locations close to the rupture will experience large dynamic motions in the direction normal to the fault, except for locations close to the epicenter of the earthquake. In contrast, the SV radiation pattern has a minimum in the direction along strike, and so the dynamic motions parallel to the fault will be small, although there may be a large static displacement in this direction.

The conditions required for directivity are less readily met in dip slip faulting. In this case, coincidence of the SH radiation pattern maximum along the slip direction and the rupture direction can only occur in the updip direction. This requires that the site be located directly updip from the hypocenter, as occurred at Pacoima Dam during the 1971 San Fernando earthquake.

We are now analyzing the systematic characteristics of the directivity effect derived from empirical analysis of recorded data and from synthetic seismogram modeling of these data.

RESULTS

Directivity Effects In Recorded Data

Directivity effects have been widely observed and modeled in the near-fault long period strong motion recordings of strike-slip earthquakes in California. Near the epicenter, at Bond's Corner and at Calexico, the fault normal motions are small and of comparable amplitude to the fault parallel motions. At the top of Figure 1, we compare the 5% damped response spectral displacements averaged for these two stations, with the average for seven stations, mostly in the El Centro array, located within 8 km of the fault but further away from the epicenter. While the stations near the epicenter have relatively small motions and a fault normal to fault parallel ratio that is close to unity at all periods, the stations located further from the epicenter along the fault have relatively large motions and a fault normal to fault parallel ratio that becomes larger than unity at about 2 seconds and reaches a factor of about 2 at 4 seconds. The ratio is unity for periods shorter than 2 sec because of the incoherence of the radiation pattern at high frequencies.
Systematic Effects of Directivity in Response Spectra of Recorded Data

Although a large database of strong motion recordings has been built up over the past several decades, we still have few strong motion recordings close to large strike-slip earthquakes. The recordings from the largest earthquakes are mostly from thrust and oblique earthquakes. However, directivity effects in thrust and oblique events are not expected to occur as frequently or be as severe as for strike-slip faulting. To demonstrate this, we categorized a suite of near-fault recordings according to whether they are from strike-slip and oblique faults (11 records from two events) or thrust (5 records from four events). The average ratio of fault normal to fault parallel motions is shown in the lower part of Figure 1 for each category. The average ratio is about twice as large for strike-slip and oblique faults (a factor of about 1.6) as for thrust faults (a factor of about 1.3). We are now using the random effects model (Abrahamson and Youngs, 1992) to discern dependencies of the absolute ground motion level and the fault normal to fault parallel ratio on the earthquake magnitude, distance, mechanism, and site category.

Modeling Of Near-Fault Long Period Ground Motions

The preliminary empirical analysis described above tends to suggest that the directivity effect close to large strike-slip faults may not be adequately represented in empirical ground motion attenuation relations. To further explore this hypothesis, we performed theoretical calculations of long period ground motions. In the course of analyses of a large number of earthquakes during the past two decades, it has been demonstrated that the principal features of long period strong ground motions recorded close to large earthquakes can be explained using simple rupture models. We computed synthetic seismograms for a magnitude 7.3 strike-slip earthquake using the synthetic seismogram method described by Hartzell and Heaton (1983). We used a fast algorithm for computing Green's functions by frequency-wavenumber integration (Saikia and Burdick, 1991). The ground motions at a site 1.5 km from the fault rupture surface were estimated by averaging the ground motions calculated for a range of different rupture scenarios. The results are compared in Figure 2 with empirical estimates derived by Idriss and by Geomatrix Consultants (Idriss, 1993). The response spectrum of the synthetic seismograms is larger than that of the empirical relations in the period range of 2.5 to 10 seconds. These calculations were done before the M=7.3 1992 Landers earthquake, which was recorded on rock at Lucerne Valley at a distance of about 1.5 km from the fault (Dennis Ostrom, Southern California Edison Company, personal communication, 1992). The average response spectral velocity recorded at this site is also shown in Figure 2. The data we show have not been instrument corrected and are thus preliminary. However, the large peak in the response at a period of 4 seconds is similar to that derived from our calculations, and exceeds the empirical attenuation relations for periods longer than about 2 seconds.

Evaluation of Parametric Uncertainty

We have made a study of the sensitivity of ground motions calculated using synthetic seismograms to ranges of parameter values used in generating the synthetic seismograms. Probability distributions were assigned to the ranges of parameter values. These parameter values include the location of the epicenter; the heterogeneous distribution of slip along the rupture; the rupture velocity; the shape of the slip function on the fault; and the duration of the slip function. The variations for each of these parameters were averaged over the location of the site along the fault rupture. The standard error of the calculated response spectra for each parameter are shown separately for fault normal and fault parallel motions in Figure 3 for a site located on rock 10 km from the rupture of a vertical strike-slip earthquake of magnitude 6.9. The fault normal motions are very sensitive to the location of the epicenter, and insensitive to the asperity distribution, whereas the fault parallel motions are moderately sensitive to each of these parameters. The motions on both components are quite sensitive to the rupture velocity.
Conclusions

Our expectation based on geometrical considerations that directivity effects are on average more important for strike-slip earthquakes than for dip-slip earthquakes was confirmed in our analysis of recorded data. Using synthetic seismogram methods to augment the sparse set of strong motion records close to large strike-slip earthquakes, we calculated larger motions than those derived from the empirical data for periods longer than 2 seconds. This supports our expectation that the empirical relations, because they are based mainly on thrust and oblique data, may underestimate the effect of directivity on long period ground motions close to large strike-slip earthquakes. The Lucerne recording of the Landers earthquake provides further support of this expectation. More extensive calculations are now being done to develop appropriate modifications of the empirical attenuation relations.

In selecting ground motion time histories for analysis of response of structures having significant response at long periods, it is important to consider whether the site is subject to directivity effects, and if so to select time histories that incorporate these effects.

Utilizing Research Results

The results of the research performed to date have been used in the estimation of strong ground motions for large bridges in California. Estimates were made for the Vincent Thomas, Schuyler Heim and Gerald Desmond bridges in Los Angeles and the Coronado Bridge in San Diego by Woodward-Clyde Consultants (1993). In these estimates, the deterministic response spectrum estimated using empirical attenuation relations derived from regression was increased at periods between 1 and 10 seconds based on the results of synthetic seismogram calculations and subsequent confirmation by the Landers recording of the 1992 Landers earthquake. Also, the difference in spectral level between fault normal and fault parallel motions was taken into account. In a study of the western San Francisco Bay Bridge for Caltrans by Geomatrix Consultants (1993), differences between fault normal and fault parallel motions were taken into account, based on an empirical analysis of recorded data by Sadigh et al. (1993) following communication of results from the present study.

REPORTS


REFERENCES


Geomatrix Consultants (1993). Seismic Ground Motion Study for West San Francisco Bay Bridge, Report to CALTRANS, Sacramento, CA.

Figure 1. (Top): Fault normal and fault parallel response spectral displacement at 5% damping for stations within 8 km of the Imperial Fault during the 1979 earthquake. Left: stations without directivity (BCR and CXO). Right: stations with directivity (EDA, E08, E07, E06, E05, E04, HVP). (Bottom): Ratio of fault normal to fault parallel response spectral displacement for thrust (left) and strike-slip and oblique (right) earthquakes.
Figure 2. (Top): Uncorrected ground velocities rotated into fault normal and fault parallel components of the Lucerne Valley record of the 1992 Landers earthquake, showing rupture directivity effect. From Dennis Ostrom, SCE. (Bottom): Comparison of 5% damped response spectra calculated prior to the 1992 Landers earthquake for a magnitude 7.25 earthquake at a distance of 1.5 km on rock with spectra estimated from two empirical relations, and with motions recorded at Lucerne Valley on rock 1.7 km from the magnitude 7.3 Landers earthquake.
Summary of Parametric Variations
Site 4 (10 km)
(averaged over epicenter and slipmodel)

Figure 3. Uncertainty in calculated ground motions, expressed as the natural logarithm of the standard error of the response spectrum, for each of the different fault parameters, shown separately for the fault normal (left) and fault parallel (right) components of motion at a distance of 10km on rock from a magnitude 6.9 earthquake.
Objective

Many of the free-field strong-motion instruments being operated in the New Madrid seismic zone (NMSZ) are installed at sites underlain by layers of poorly and semi-consolidated soils of varying thicknesses. In the northwestern corner of Tennessee, for example, the depth to the top of the Paleozoic bedrock is in excess of 750 m, whereas in the northwestern corner of Kentucky the depth to the top of bedrock is typically on the order of 100 m. From experience and the depositional nature of the soils, it is known that the elastic properties of the soils vary laterally as well as vertically. Consequently, it is reasonable to believe that the soil columns underlying the strong-motion stations are inducing strong site effects into the recordings. The objective of this study is to use conventional seismic reflection and refraction techniques to characterize the major velocity units of the soil column at a selected group of free field accelerometer sites in the NMSZ.

Results

Figure 1 illustrates the geographical locations of the strong-motion installations investigated for this study. Seismic data were collected at the sites using the walkaway technique, which consists of stepping the energy source out a fixed geophone spread. 40 Hz vertical component geophones were used for collecting P-wave data, and 4.5 Hz horizontally polarized geophones for collecting SH-wave data. Geophone spacing was either 3.05 m (10 ft) or 6.1 m (20 ft), depending on the depth to be investigated. For most of the sites investigated, a 12-channel floating point seismograph was used. Exceptions occurred at sites LATN, RIDG, and VSAB, where a 24-channel fixed point seismograph was used to record the P-wave data. Energy sources used were a 7.3 kg seismic hammer for generating SH-waves, and a vacuum assisted weight drop for generating the P-waves.
Figure 2 shows the soil columns at the ten sites investigated. Velocities and thicknesses of the shallower layers were generally derived from first-arrival SH-waves, whereas the characteristics of the intermediate and deeper layers were derived from SH- and P-wave reflections. $Q_s$ values given for the velocity layers were either derived using pulse broadening techniques, or estimated using the relationship:

$$Q_s = 0.078 V_s + 6.986$$

(Wang et al., 1992, 1993). Estimated $Q_s$ values are enclosed by parentheses. Final interpretations of the data will be given in Technical Report for this project.

REFERENCES


Bedrock * interval velocity

Figure 2-B
Investigations

1. Data Collection. The Incorporated Research Institutions for Seismology (IRIS) have designated the Albuquerque Seismological Laboratory (ASL) to be a data collection center (DCC) for a global network of digitally recording seismograph systems (the Global Seismograph Network or GSN). Some 70 seismograph stations around the world send data (typically via magnetic computer tape) directly to the ASL for processing.

2. Data Processing. All of the data received from stations of the GSN and other contributing networks is read, reviewed, checked for quality, and archived at the ASL.

3. Data Distribution. After the data collection and quality review, all of the data are assembled into network volumes which are distributed to regional data centers and other government agencies.

Results

1. Data Collection. IRIS has an ongoing program to deploy over 100 seismograph stations around the world. The USGS has been assigned the task of installing and maintaining many of these stations and processing the digital data they produce. At present, the ASL maintains and receives data from roughly 40 IRIS stations. The ASL will install roughly 10 to 20 new stations per year, for at least the next two years. In addition to the 40 IRIS stations, the ASL DCC receives data from 4 stations of the Global Telemetered Seismograph Network, 2 SRO/ASRO stations, 4 DWWSSN stations, and 13 stations from the TERRAscope network in Southern California. Thus the total number of stations for which the ASL has direct responsibility includes some 70 stations. At present, each of the IRIS stations produces roughly 5 to 8 megabytes of compressed seismic data per day. To keep up with this data flow, IRIS has funded the purchase of new hardware at the DCC. This hardware has included an optical disk jukebox, for archival storage of the data, backup power systems, and computers (both workstations and servers). In addition to the 70 stations for which the ASL has primary responsibility, data is received from 17 stations of the IRIS/IDA network (supported by the University of California, San Diego). The IRIS/IDA data arrives pre-processed by the IRIS/IDA DCC, so this data is ready to be archived, with little intervention by the ASL DCC.

2. Data Processing. The current data flow into the DCC amounts to a daily total of approximately 400 to 500 megabytes. This data is reviewed for quality, which primarily consists of checking for timing and hardware problems. When problems are detected, the appropriate ASL Field Engineers or station personnel are notified, so that the problem may be rectified. After quality control, the data are reformatted into a uniform format and are stored on
optical disks. In addition to our own quality control program, the DCC also responds to any data problems reported by seismologists who are using the data.

3. Data Distribution. For data distribution, the ASL DCC acts much like a data wholesaler, by delivering data to regional data centers. The regional centers act much like data retailers, by distributing data to individual seismologists. The primary means of delivering data to the regional data centers is via SEED (Standard for the Exchange of Earthquake Data) format network volumes. The network volume program is a continuing program which assembles all of the data recorded by all of the above listed networks for a specific calendar day or days onto one magnetic tape. This tape includes all of the necessary auxiliary information (station parameters, calibration data, transfer functions, time corrections) for each station on the tape. All of the data on these network volumes are written in SEED format (a standard format developed by the USGS in cooperation with other organizations) and copies are distributed to several university and government research groups for detailed analysis and further distribution. These tapes are assembled approximately 60 days after real time in order to provide sufficient time for the data to be recorded at the station, mailed to the ASL, and processed at the DCC.

In addition to the network volumes, special data volumes are created several times per week which contain all recently arrived data. These special volumes are sent to the IRIS Data Management Center (DMC) where the data is freely accessible to scientists all over the world with the minimum possible delay.

The ASL DCC is also involved in two special data distribution projects. In the first project, data collected by the ASL in the time period 1980-1987 are being reformatted and re-released in the modern SEED format. Republishing this data in a modern format will facilitate the use of this data by many seismologists. In the second project, the ASL is cooperating with the USGS National Earthquake Information Center, the IRIS DMC, and the Federation of Digital Seismograph Networks, to publish on CD-ROM the data from the most important earthquakes throughout the world. Publication on CD-ROM will make this data even more accessible to the international seismological community.
Earthquake Hazard Studies, Metropolitan Los Angeles-Western Transverse Ranges

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Investigations and results:

Our objective is a complete digital geologic map of the Los Angeles 1:100,000 (1 degree x 30-min.) sheet in order to display detailed geology and structural history at a "regional" scale. We compile digitally, at 1:24,000, the geology of 32 (7.5-min. x 7.5 min.) individual quadrangles included in the Los Angeles sheet from the best modern sources, mosaick these quads and then reduce digitally. Each of the 1:24,000 quadrangles contains eight digital layers in color: 3 for the base, geology, structure, unit labels, exploratory wells, and fossil localities. Focussing on the west half of the sheet, preliminary maps of 12 quadrangles have been completed (from northwest to southeast): Newhall, Moorpark, Simi, Santa Susana, Oat Mtn., Newbury Park, Thousand Oaks, Calabasas, Canoga Park, Point Dume, Malibu, and Topanga. Four of these 12 have been released in open file (Calabasas, Canoga Park, Oat Mtn., and Thousand Oaks), and two are in review (Santa Susana and Topanga). Compilation proceeds on Val Verde, and revisions continue on several other quads.

The 16 quadrangles have also been mosaicked at 1:75,000 (1:100,000 next), with geology where available, using a uniform color scheme across the map, in order to evaluate structural history, regional aspects of the geologic interpretations and to test the effects of digital reduction. Abstracts have been submitted describing the mosaicking technique and products for 1994 meetings of the Cordilleran Section of GSA, and Pacific Section of AAPG.

Field investigations have resulted in the first-ever stratigraphic subdivision, with map, of the Upper Cretaceous Tuna Canyon Formation (Santa Monica Mts., Topanga quadrangle; see Alderson, 1988)*. On request, we have furnished to National Park Service digital files for geologic maps of several 1:24,000 quadrangles in the Santa Monica Mountains.

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*Alderson, J. M., 1988, New age assignments for the lower part of the Cretaceous Tuna Canyon Formation, Santa Monica Mountains, California (abs.): Geol. Soc. America Abs. with Progs., vol. 20, no. 3, p. 139.

Reports:


Campbell, R. H., and Yerkes, R. F., Structural geology in the western part of the Los Angeles 100k sheet (abs.): submitted to Pac. Sec., AAPG for Apr. 1994 meeting in Ventura, CA.

Yerkes, R. F., and Campbell, R. H., SCAMP: West half of Los Angeles 1:100,000 Sheet (abs.): submitted to Cordilleran Sec. GSA for Mar. 1994 meeting in San Bernardino, CA.
1.0 INTRODUCTION

Water system operation is critical following an earthquake. Immediately after an earthquake, water will be necessary for fire fighting purposes. Longer term, water will be necessary for public health and industrial needs.

Earthquake hazard maps can be used as tools to help assess seismic vulnerability of water systems. Earthquake hazard maps can also be used as site planning tools for these systems. In the Pacific Northwest, earthquake hazard maps have been prepared by the following agencies:

- United States Geological Survey (USGS)
- Washington State Department of Natural Resources, Division of Geology and Earth Sciences
- Oregon Department of Geology and Mineral Resources
- Idaho Geological Survey
- Local public agencies such as the Seattle Water Department

Unfortunately, many smaller water system utility operators in the Pacific Northwest are unaware of the availability of earthquake hazard maps, or how to obtain and use these maps. In order to make this information available, Kennedy/Jenks Consultants developed a workshop syllabus and accompanying guide document on how to use earthquake hazard information to assess water system seismic vulnerability. Available earthquake hazard information was then obtained for various areas of the Pacific Northwest, and seven
seminars were presented to water utility operators throughout the Pacific Northwest. Additionally, individual technical assistance on obtaining and applying hazard information was provided to small communities.

2.0 SEMINAR MATERIALS

The seminars addressed vulnerability of all water system components to earthquake hazards. A syllabus was developed that covered the different aspects of water system seismic vulnerability and loss mitigation. A comprehensive set of slides was then developed. As a future reference for conference participants, a course manual was also prepared.

2.1 Syllabus

The course syllabus included:

1. Introduction
2. Seismicity and Seismic Hazards
3. Water Supply System Seismic Vulnerability
   - Sources
   - Treatment Plants and Pumping Stations
   - Pipelines
   - Storage Tanks and Reservoirs
   - System Monitoring and Control
4. System Vulnerability Assessments
5. Earthquake Hazard Information
6. Seismic City Water System Vulnerability Assessment
7. Emergency Planning
8. Selected References

In addition to lectures and slide presentations on water system seismic vulnerability, interactive sessions were included as part of the course syllabus. These sessions were designed so that seminar participants could apply the information presented during the lectures.

During the first interactive session, seminar participants performed a seismic vulnerability assessment of a hypothetical water system. A map of the hypothetical water system, earthquake hazard information, and water system component characteristics were provided. Seminar participants then identified vulnerable components and features of the system and developed loss mitigation recommendations.
During the second interactive session, seminar participants either provided maps of their systems or drew diagrams of their systems on overhead charts. Based on the system descriptions and seismic vulnerability information presented during the seminar lectures, potentially vulnerable facilities were identified on a preliminary basis.

### 2.2 Slide Set

In order to complement the lectures and show seminar participants the effects of earthquake hazards on water system components, a slide set containing in excess of 200 slides was prepared. Although the slide set contains some slides that show only text or diagrams, the majority of the slides are pictures of earthquake hazards and earthquake effects on water system facilities. Most of the slides are from post-earthquake reconnaissance visits made by the principal investigator or others to sites in the United States, the Philippines, Turkey and Costa Rica. Slides from the principal investigator’s trips to Japan on Japanese earthquake preparedness measures were also included in the set. Additional slides were obtained from the Federal Emergency Management Agency (FEMA) and the Oregon State Department of Geology and Mineral Industries (DOGAMI).

### 2.3 Guide Document

The guide document *Earthquake Vulnerability of Water Systems* was provided to all seminar participants. The guide document presents the information from the lectures and shows pictures of many of the slides. Consequently, the guide document can be used as a reference for water system utility personnel.

In addition to all seminar participants, the guide document was distributed on request to those not attending the workshop. Copies of the document were also provided to water agencies in Japan and the Philippines during the visits to those countries by the principal investigator. The American Water Works Association (AWWA) plans to publish the document so that it will be available to water system personnel nationwide.

### 3.0 HAZARD INFORMATION SURVEY

Earthquake hazard information for the Pacific Northwest was obtained from federal and state governmental agencies. Specific agencies included the following:

- United States Geological Survey
- Idaho Geological Survey
- Oregon Department of Geology and Mining Industry
- Washington State Department of Natural Resources, Division of Geology and Earth Resources

Earthquake hazard maps were obtained from these agencies for the area of each seminar. When earthquake hazard mapping was not available, geologic maps were obtained. The
maps were presented during the seminars to make participants aware of their existence and how they could be obtained. The maps were also used to show how earthquake hazard areas could be identified.

4.0 SEMINARS

The seminars were presented in conjunction with the Pacific Northwest Section of AWWA. Each AWWA subsection was contacted to see if they would be interested in hosting a seminar. Seven subsections agreed to host seminars. The seminars are summarized in Table 1.

5.0 TECHNICAL ASSISTANCE FOR SMALL COMMUNITIES

Individualized technical assistance was provided to those seminar participants that requested additional help. In most instances, system descriptions provided by participants were used to identify critical water system components and potential seismic hazards that could adversely affect those components. Sources and availability of appropriate earthquake hazard and geological maps were identified for these systems.

Additionally, officials from several cities requested and received more detailed assistance. Steps needed to implement a detailed seismic vulnerability assessment of their systems were defined and described.

<table>
<thead>
<tr>
<th>AWWA Subsection</th>
<th>City, State</th>
<th>Date</th>
<th>Participants</th>
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<tr>
<td>Lower Columbia</td>
<td>Oregon City (Portland), Oregon</td>
<td>24 June 1993</td>
<td>53</td>
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<tr>
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<td>Coos Bay, Oregon</td>
<td>31 August 1993</td>
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<td>Kenniwick, Washington</td>
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<td><strong>163</strong></td>
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</table>
Investigations

1. **NEIC reporting services.** The NEIC now uses broadband data to routinely compute source parameters such as depth from differential arrival times, radiated energy of an earthquake, and arrival times of late-arriving phases. These parameters are published in the Monthly Listing of the Preliminary Determination of Epicenters and in the Earthquake Data Report. Algorithms for these operations are being modified so that determination of broadband depth and radiated energy can be accomplished rapidly enough for public dissemination through the Quick Epicenter Determination and the Preliminary Determination of Epicenters.

2. **Effects of Earth structure on source parameters.** To improve the accuracy of source parameters derived from waveform analysis, we are developing corrections for the effects of wave propagation in the Earth.

   A. **Body wave interactions with upper mantle structure.** With the proliferation of digitally recording broadband networks around the world (including the USNSN), new techniques must be developed for the interpretation of seismic phases recorded at regional distances. We are generating a database of synthetic seismograms of body wave interactions with various upper mantle models of the Earth. A comparison of the differences in the theoretical seismograms will be used to infer regional upper mantle structure.

   B. **Effects of pulse distortion on reading arrival times of non-minimum travel-time phases.** From both theory and observation, it has been well documented that waveforms of body waves that propagate past internal caustics suffer severe phase distortion. The accuracy and/or resolution of tomographic inversions involving such phases may be affected by the accuracy with which arrival times of these phases are read.

   C. **Effects of attenuation on the computation of source parameters.** We are developing techniques to determine the depth- and frequency-dependence of attenuation in the Earth. Resolution of this frequency dependence requires analysis of a continuous frequency band from several Hz to tens of seconds. It
IV

also requires consideration of the contributions of scattering and slab diffraction to apparent broadening of a pulse.

D. Use of differential travel-time anomalies to infer lateral heterogeneity. We are investigating lateral heterogeneity in the Earth by analyzing differential travel times of phases that differ in ray path only in very narrow regions of the Earth. Because such phases often are associated with complications near a cusp or caustic, their arrival times cannot be accurately read without special consideration of the effects of propagation in the Earth as well as additional processing to enhance arrivals.

3. Rupture process of large- and moderate-sized earthquakes. We are using digitally recorded broadband waveforms to characterize the rupture process of selected intraplate and subduction-zone earthquakes. The rupture processes thus delineated are used to complement seismicity patterns to formulate a tectonic interpretation of the epicentral regions.

Results

1. Reporting Services. The NEIC now uses broadband waveforms routinely: (1) to resolve depths of all earthquakes with $m_b > 5.8$; (2) to resolve polarities of depth phases to help constrain first-motion solutions; (3) to present as representative digital waveforms in the monthly PDE's; and (4) to compute the energy radiated by earthquakes. In the Monthly Listings of the PDE covering the interval August 1992 to July 1993, depths using differential arrival times from broadband waveforms were computed for 124 earthquakes; radiated energies were computed for 133 earthquakes. An algorithm for rapid retrieval of data from the USNSN and selected GSN stations has been successfully tested. Broadband depths of 17 earthquakes were obtained by rapid determination and included in the QED and the PDE during this test period.

2. Effects of Earth structure on source parameters.

A. Body wave interactions with upper mantle. Synthetic seismograms generated for P and S waves interacting with the upper mantle are sensitive to differences in velocity contrasts, velocity gradients, and attenuation at the 420- and 670-km discontinuities. Major contributions to waveform shape come from later arrivals such as interference head waves and cusp-diffracted waves. In waveform data with sufficient broad bandwidth, these features can be identified and used to infer acceptable models of the upper mantle. A Langer locked-mode method of synthesizing seismograms for local distances is being adapted for computation of synthetics out to regional distances.

B. Arrival times of pulse-distorted body waves. Body waves that touch internal caustics in the Earth are distorted in a way that can be mathematically corrected by Hilbert transformation. As a significant amount of teleseismic data used by the NEIC is in digital form, this correction can now be routinely
performed. An automated processing package combining the methods of Choy and Richards (1975) and Harvey and Choy (1982) is now being implemented to obtain distortion free broadband waveforms for routine processing by NEIC analysts.

C. Attenuation in the Earth. We are attempting to separate intrinsic attenuation from scattering in waveforms. We synthesize waveforms using a method that simultaneously models causal attenuation and source finiteness. Under the assumption that intrinsic attenuation can be described by minimum phase operators, we can attribute discrepancies in the waveforms to scattering.

D. Lateral heterogeneity from differential travel times. We are using a source-deconvolution technique to resolve differential travel times of body waves near cusps and caustics. Application of this algorithm to PKP waves sampling the inner core suggests that regional velocity variations exist within the upper 200 km of the inner core. In reading high-quality arrival times of branches of PKP, we are correcting for pulse distortion in the AB arrival. The accumulation of these data can be used to determine if pulse distortion phenomena have biased the historical catalogs which have seen extensive use lately in deriving models of lateral heterogeneity.

3. Rupture processes.

A. Radiated energy has been computed for over 400 earthquakes. The accumulated results are being summarized in a paper describing and mapping global patterns of radiated energy release and apparent stress.

B. Moderate-sized compressional earthquakes occurring in the outer rise have been observed to precede some large subduction-zone earthquakes. We are developing a methodology for using these possibly precursory events to constrain the state of stress seaward of large earthquakes prior to their rupture. Preliminary results from modeling an outer-rise earthquake that preceded the large 1985 Valparaiso earthquake indicate that the outer-rise earthquake was induced by an elevation of stress seaward of the interplate asperity of the 1985 Valparaiso earthquake.

C. Source parameters for moderate-sized North American earthquakes from broadband analysis are determined on request and given to the U.S. Earthquake Project for publication in its open-file reports. The depth, focal mechanism, and moment rate function were determined for the Scott’s Mill earthquake of March 25, 1993.

Reports


United States Earthquakes

9920–10042

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Investigations

During the period October 1, 1992 through September 30, 1992, we conducted canvasses by mail questionnaire for information on damages and felt effects from 539 earthquakes. Two hundred and three of these shocks occurred in Alaska, 7 in Arizona, 5 in Arkansas, 185 in California, 1 in Canada near New York, 5 in Colorado, 1 in Guam, 7 in Hawaii, 13 in Idaho, 1 in Illinois, 7 in Maryland, 2 in Massachusetts, 1 in Michigan, 1 in Minnesota, 1 in Mississippi, 9 in Missouri, 2 in Montana, 1 in North Carolina, 2 in Nebraska, 15 in Nevada, 1 in New Hampshire, 1 in New Jersey, 4 in New Mexico, 3 in Oklahoma, 15 in Oregon, 5 in Pennsylvania, 5 in or near Puerto Rico, 2 in South Carolina, 1 in South Dakota, 3 in Tennessee, 12 in Utah, 5 in Washington, and 13 in Wyoming.

Field surveys of damage were made by Glen Reagor and Frank Baldwin for the March 25, 1993, Scotts Mills, Oregon, earthquake and by Jim Dewey for the September 21, 1993 (September 20, local time) Klamath Falls, Oregon, earthquakes.

We continue to update data bases on the Earthquake Data Base System (EDBS) and to furnish seismic data to engineers, land-use planners, architects, oil company geophysicists, insurance companies, university programs, and private citizens.

Results

Nine earthquakes caused damage (MM VI or greater) in the United States and its dependencies during the period covered by this report. Two of these shocks were in Alaska, 2 in California, 1 in Guam, 1 in Mississippi, and 3 in Oregon.

The Scotts Mills, Oregon, earthquake of March 25, 1993, produced effects corresponding to a Modified Mercalli Intensity of VII. The magnitude 5.4 (MS, USGS) earthquake was felt over an area of approximately 97,000 square kilometers. The most severe damage occurred to old (pre-1950), unreinforced masonry buildings. A highway bridge was damaged; one end of a span dropped, leaving a 6 to 8 inch (15 to 20 cm) vertical offset between that span and the adjacent span. Area newspapers noted four cases of people needing medical attention for minor injuries.
suffered in the earthquake and three cases of people needing attention for inhalation of noxious fumes arising from chemicals spilled in the earthquake.

The magnitude 8.1 (MS, USGS) Marianas Islands earthquake of August 8, 1993, located near the island of Guam at a depth of approximately 60 km, produced intensity VII effects at many locations on Guam and pockets of intensity higher than VII. Three high-rise hotels at Tumon Bay, Guam, suffered damages corresponding to intensity IX. Cracks hundreds of feet long and one to two feet wide, caused by liquefaction in the underlying soil, damaged facilities at the commercial port and U.S. Naval Base at Apra Harbor. Forty-eight people were treated for earthquake-caused injuries at Guam Memorial Hospital.

The Klamath Falls earthquake sequence of September 21, 1993 (September 20, local time) included shocks of magnitude respectively 5.8 and 5.7 (MS, USGS) and produced effects corresponding to intensity VII in the epicentral region and at Klamath Falls, about 20 km from the epicentral region. The earthquakes were felt over an area of approximately 131,000 square kilometers. As in the Scotts Mills, Oregon, earthquake of March 25, most of the damaged structures were of unreinforced masonry and built prior to 1950. More recently constructed buildings that experienced damage included an addition to the Klamath County Courthouse and two buildings on the campus of the Oregon Institute of Technology. One person died when his car was crushed by a boulder in an earthquake-induced rockfall, and one person died of a heart attack apparently triggered by one of the earthquakes.

During this reporting period, seismicity searches on the EDBS were provided to 189 users, of whom 29 were with U.S. Government agencies and 45 with domestic or foreign universities. One hundred and fifteen searches were conducted for commercial entities or individuals.

The following catalogs in the EDBS (listed by the abbreviation with which they are accessed in the EDBS) were added or updated during the 1993 fiscal year:

**BC** Covering the European Community plus Switzerland and Austria. Lists earthquakes with intensities IV and above. Covers the period 1479–1983. Originally assembled by J.M. van Gils and revised by G. Leydecker (Federal Institute for Geosciences and Natural Resources, Hannover, Germany).


**ISC** Catalog of earthquakes located worldwide by the International Seismological Center, now updated through April 1991.


PDE Catalog of epicenters located worldwide by the National Earthquake Information Center. Updated weekly and monthly.

USHIS Covering the 50 states of the United States, 1578–1989. For most states, includes earthquakes with magnitudes 4.5 or greater or with intensities of VI or larger. For Alaska and areas offshore of California, Oregon, and Washington, the lower magnitude threshold is 5.5. Prepared from Stover and Coffman (1993).

Work is in progress on the Global Hypocenter Data Base CD-ROM, Version 3.0.

Reports

PREPARATION OF PUBLIC-INFORMATION PRODUCTS
FROM NEHRP RESEARCH RESULTS, WASATCH FRONT, UTAH

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1434-93-G-2342
Program Element IV.2

After nearly a decade of intensive research under the National Earthquake Hazards Reduction Program (NEHRP) in Utah, much new information is now available for use in public policy-making, reducing geologic hazards and risk, and increasing public awareness. The most effective way to get the appropriate information to specific user groups is to produce publications tailored to their needs. The objective of this project is to provide publications for the general public, including homebuyers and real-estate agents.

The Utah Geological Survey (UGS) is producing four specific public-information products: (1) a homebuyer’s guide to earthquake hazards, (2) a full-color brochure describing and illustrating Utah’s most active fault, the Wasatch fault, (3) a pamphlet "translating" information on the ground-shaking hazard in Utah, and (4) a series of page-size liquefaction-potential maps for Wasatch Front counties. These products will be published as UGS Public Information Series publications, and distributed free-of-charge. The UGS will also publish as contract reports, the NEHRP-funded liquefaction-potential maps and reports prepared by Utah State University and Dames and Moore, Inc., that are complete but not widely available.

As of September 1993, the contract reports are in press. The page-size liquefaction-potential maps are soon to be digitized and accompanied by a translated text that is in draft form. Research, writing, and photography continues for the other publications.
Global Seismicity Mapping

9920-10242

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Investigations

State/Regional Seismicity Maps. Produce and distribute seismicity maps on shaded, elevation-tinted map bases.

Results

State Seismicity Maps. The aim of the seismicity maps is to provide the most complete picture possible of where earthquakes have occurred historically in relation to geographic, geomorphic and cultural features. This is accomplished by selecting or compiling an earthquake database that is then plotted and printed on a shaded, elevation-tinted base map.

Since this project began in 1988, seismicity maps have been completed for Alaska, California, Hawaii, Utah, Southern California, and the U.S. Similar maps are currently underway for California/Nevada and Washington/Oregon. The California/Nevada map will display over 160,000 earthquakes located by regional networks from 1987-1992. Rupture areas of large earthquakes will also be plotted.

The earthquake database for the Washington/Oregon map is still being compiled from numerous local and regional networks. This map is being produced at the same scale and projection as the California/Nevada map so that the two maps may be joined, if desired.

The resulting maps will be distributed to the research community worldwide, as well as to numerous educational institutions in the U.S. They will also be available for public purchase.
Seismic Review and Data Services

9920–67032

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Investigations

This project distributes copies at cost of filmed seismograms from the World­wide Standardized Seismograph Network (WWSSN), the Canadian Standard Network (CSN), and various stations with historical (pre-1963) records.

Results

Copies of CSN seismograms on 35mm reels were received on schedule from the Geological Survey of Canada. No films of historical seismograms were added to the archives this year.

The number of active stations in the WWSSN continues to decline, partly as a result of the replacement of the 1960 vintage analog seismographs with modern broadband digital systems. The quality of the recent data from the active WWSSN stations is still very good because these stations are operated by well-trained staffs. Many of the closed or inactive stations were beset with financial, political, or cultural encroachment problems.

We have ceased microfiling original seismograms. We will continue to copy existing microfiches as needed. Changes in branch funding required a price increase in fiscal 1993 to $0.50 per fiche.

We received 30 special orders for films, ranging from a few to several thousand seismograms. Approximately 6,450 filmed seismograms were copied and distributed to fill the orders.
Probabilistic Earthquake Assessment

9920-80832

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Investigations

Stuart Nishenko worked on probabilistic earthquake forecasts for the Wasatch Front, Utah with D. Schwartz (USGS, Menlo Park), an evaluation of the reliability of various types of probabilistic earthquake forecasts with D. Perkins (USGS, Golden), and a rebuttal to the Kagan and Jackson paper on seismic gaps (JGR, 1991, 96, 21419-21431) with L. Sykes (L-DGO, Palisades, NY).

James Dewey worked with J. Healy (USGS, Menlo Park) and V. Kossobokov (International Institute for Earthquake Prediction Theory and Mathematical Geophysics, Moscow, Russia) to formulate and describe a test of the M8 earthquake prediction algorithm.

C. Bufe worked on a G.K. Gilbert Fellowship with D. Varnes (USGS, Golden, Colorado) during most of the reporting period, exploring the application of nonlinear dynamics to earthquake sequences. He also worked with S. Nishenko and D. Varnes on completion of analysis of large earthquake potential and current seismicity trends in the Alaska-Aleutian region.

C. Bufe, in cooperation with OIG, prepared information brochures and conducted advance planning for the 3rd annual international training course, “Understanding Earthquakes and Mitigating Their Effects.” Although the previous two training courses had been well received and critically acclaimed, the 3rd course, planned for May 1994, had to be cancelled when anticipated external funding was not received.

Though clearly not within the domain of OEVE studies, J. Evernden was requested by C. B. Archambeau to review and evaluate a study co-authored by Archambeau relative to the geological and geophysical factors affecting the safety of the proposed nuclear waste repository at Yucca Mountain, Nevada. Such a review was approved by the Branch Chief (BEGI).
Evernden has continued to generate new versions of his ground motion programs. These are the only programs available on a worldwide basis that actually predict strong motion values, values which agree with observations. One need only generate, via any means available, a digitized geologic map of an area of interest in rasterized form, establish the correlation between lat/long and pixels, determine the regional attenuation parameter via study of local earthquakes, and one is in business. If one is willing to settle for evaluation of motion on regions of uniform ground condition (four different values), present products are immediately applicable throughout the world.

Results

S. Nishenko and Lynn Sykes (L-DEO) completed a rebuttal to the Journal of Geophysical Research article by Kagan and Jackson on seismic gaps (JGR, 1991, v. 96, p. 21419). Half of the earthquakes that Kagan and Jackson use to test the seismic gap hypothesis do not correspond to the selection criteria of Kelleher, Sykes, and Oliver (1973, JGR, v. 78, p. 2547) or McCann et al. (1979, Pageoph, v. 117, p. 1082). Given the relatively small number of eligible earthquakes that occurred during the interval 1973–1992, the hypothesis test proposed by Kagan and Jackson does not yet have the power to adequately differentiate between alternative models at a high level of confidence. Presentations were given at the University of Alaska, Wadati Conference on Great Subduction Earthquakes (September 16–19, 1992) and at the Fall 1992 AGU meeting in San Francisco, Calif. The initial phase of data collection and analysis of the reliability of probabilistic earthquake forecasts was conducted by S. Nishenko and D. Perkins (BELH).

S. Nishenko worked with B. Atwater, A. Nelson (USGS), G. Carver (Humboldt State College), and others to develop a consensus statement about the likelihood of great and giant earthquakes along the Cascadia subduction zone.

S. Nishenko organized and co-chaired (with J. Ebel, Boston College, Weston Observatory) a working group meeting on Northeastern United States Earthquake Probabilities at MIT, April 28–29, 1993. These meetings are intended to develop a consensus statement about earthquake hazards in the northeastern United States and lay the groundwork for a joint USGS/FEMA/NESEC (New England States Earthquake Consortium) workshop on earthquake hazards and risk in FY 1994.

J. Dewey worked on preparing a rationale and description of the M8 test that is now being conducted jointly with Healy and Kossobokov. The test is described in a USGS Open-File Report.

C. Bufe completed analysis of recent (post-1964) seismicity trends in the Alaska-Aleutian region. Time-to-failure analysis was applied to accelerating seismic release patterns in the Shumagin Islands, Alaska Peninsula, Delorof Islands,
and Kommandorski Islands segments. Results were reported at the Wadati Conference on Great Subduction Earthquakes and in a paper submitted to Pure and Applied Geophysics.


Both J. Evernden and S. Nishenko worked on the development of interactive, strong-ground motion programs and ground condition maps for the counties of Weber, Davis, Salt Lake, and Utah along the Wasatch Front, Utah. These products will initially be used in conjunction with the FEMA emergency response exercise, RESPONSE 93.

S. Goter and S. Nishenko finished a 2-year renovation of the NEIC Visitors’ Center in Golden, Colorado.

J. Evernden completed his evaluation of the study by Archambeau and associates on geological and geophysical factors affecting the safety of the proposed nuclear waste repository at Yucca Mountain, Nevada. The review was completed with the assistance of several USGS geologists and published as an USGS Open-File Report. The report refutes the conclusions of Archambeau and others with regard to certain factors affecting the safety of the site.

J. Evernden’s ground motion programs have been distributed to Russia and Armenia at a recent international meeting in Armenia. Evernden demonstrated that if those who have studied the Spitak earthquake had understood the effects of differing regional attenuation (i.e., not evaluated that earthquake and its effects at Yerevan in terms of the California experience) they would have not been surprised by what happened at Yerevan. The Russians used 0.2 g as an appropriate 90 percentile value, while a properly calibrated model using relevant ground conditions clearly establishes that the 90 percentile value at Yerevan should have been assumed to be 1.25 g or greater.

J. Evernden has also demonstrated, via the use of worldwide strong motion data, that there is a fixed quantitative relation between intensity and maximum velocity, and that maximum acceleration increases, at a given intensity, with decreasing regional attenuation. The latest versions of the ground motion programs are now ready for distribution.

Reports


Evernden, J.F., and S.P. Nishenko, 1992, Programs for prediction of ground motion resulting from worldwide earthquakes [abs.]: EOS, (American Geophysical Union, Transactions), v. 73, p. 73.


Nishenko, S.P., and Sykes, L.R., 1992, Seismic gap hypothesis test [abs.]: EOS (American Geophysical Union, Transactions), v. 73, p. 365.

Investigations

The purpose of this project is to provide the day-to-day management and systems maintenance and development for the Golden Data Processing Center. The center supports Branch of Earthquake and Landslide Hazards with a variety of computer services. The systems include a PDP 11/70, a VAX/750, a VAX/780, two MicroVAX’s, two SUN servers, 5 SUN workstations, and a PDP 11/34. Total memory is 40 mbytes and disk space is approximately 7 G bytes. Peripherals include four plotters, ten mag-tape units, an analog tape unit, two line printers, 5 CRT terminals with graphics, and a Summagraphic digitizing table. Dial-up is available on all the major systems and hardwire lines are available for user terminals on the upper floors of the building. Users may access any of the systems through a Gandalf terminal switch. Operating systems used are RSX11 (11/34’s), Unix (11/70), RT11(LSI’s) and VMS (VAX’s).

Results

Computation performed is primarily related to the Hazards program; however, work is also done for the Induced Seismicity and Prediction programs, as well as for DARPA, ACDA, and U.S. Bureau of Reclamation, among others.

The data center supports research in assessing seismic risk and the construction of national risk maps. It also provides capability for digitizing analog chart recordings and maps. Also, most, if not all, of the research computing related to the hazards program are supported by the data center.

The data center also supports equipment for online digital monitoring of Nevada and Colorado Western Slope seismicity. Also, it provides capability for processing seismic data recorded on digital cassette tape in various formats.

The computer center manages the local area network (LAN) providing central backup facilities, file services, and peripheral access for about 75 personal computers. This LAN management is accomplished with Path Works software.
Investigations

We are compiling an improved catalog of historic felt and damaging earthquakes in Washington and Oregon based on existing earthquake catalogs (published or unpublished), supplemented by contemporaneous newspaper clippings, diary entries, references to articles in scientific journals, and other available information. Our new catalog takes advantage of powerful relational data-base features to store extensive information on each event and to allow the user to view the information in various ways; from a single-line summary to a complete report including all known sources of information for an earthquake.

Our catalog is being constructed using a PC data-base product. For each cataloged earthquake, the data-base will also contain a "scrapbook" of original source materials. The first step in constructing the catalog has been to enter existing catalogs, newspaper clippings, etc. into the "scrapbook". As we create the scrapbook we index the material by tabulating as much specific information as possible from each source (date, location, etc.). This tabulation is used to help us to identify sources of information for each earthquake. After reviewing the various sources, we select the best information to create the improved and more comprehensive catalog of historic earthquakes in Washington and Oregon.

Progress

During this contract period, we acquired a PC and data-base software. Because we had developed the data base design earlier, our objectives were well defined; beginning with data entry, and proceeding through tabulation, compilation of information by earthquake date and time, and ending with the selection of the best available magnitude, time, location, and depth for each event. The major concentration so far has been entering and tabulating data. We have also been developing tools that allow us to view the data in ways which facilitate each step of the procedure, and which check for various types of errors. Currently we have entered and tabulated most existing catalogs, and a sizable volume of newspaper and periodical accounts which we have collected over some years. We have also reviewed additional newspaper indices and original data sources, such as microfilmed copies of the original handwritten comments of weather observers, to see whether additional information can be gleaned.
Investigations

The objective of this project is to provide computer graphics services (such as access to Geographic Information System (GIS) software) to USGS geological hazards investigators. These services include (1) consultation on digital spatial data base design and data acquisition, (2) training in the use of GIS methods, (3) assistance in the assembly of large spatial data sets, and (4) research into advanced spatial data analysis topics. In addition, the Laboratory manages a large Geological Hazards Data Base and assists in producing outreach products that require advanced graphics technologies. Personnel associated with this project are: S. R. Brockman, J. A. Michael, and A. Tarr.

Specific investigations conducted during Fiscal Year 1993 were (1) Geologic Hazards Data Base, (2) Central U.S., Pacific Northwest, and California earthquake hazards data, (3) Colorado geologic hazards data, (4) Quaternary faults, and (5) Laboratory expansion.

Results

Geologic Hazards Data Base -- During FY 1993, the Geologic Hazards Data Base was managed and maintained by the Computer Graphics Laboratory in Golden, Colorado for the benefit of projects supported by the National Earthquake Hazards Reduction and Landslide Hazards Programs in the Central U.S., Pacific Northwest, California, and Colorado. The data in the Data Base consist principally of on-line ARC/INFO coverages and off-line native format data tapes containing USGS Digital Line Graph (DLG), Digital Elevation Model (DEM) files, and SPOT image files. The on-line data consist of working ARC/INFO coverages (approximately 1200 MB) and archived ARC/INFO coverages (approximately 500 MB). The archived coverages have been released by authors for informal distribution to other researchers while the working data are subject to revision and are only available by agreement with the authors. The on-line ARC/INFO data are accessible to local researchers over a LAN and to authorized remote users over Internet; in addition, the archived data sets are available to other research groups via anonymous ftp. For security reasons,
the on-line data backup tapes and all the off-line data tapes are stored in a vault at the Central Region GIS Lab at the Denver Federal Center.

It is planned that in FY 1994 parts of the Geologic Hazards Data Base will become available as part of the National Spatial Data Infrastructure (NSDI), a major initiative proposed by the Federal Geographic Data Committee. The Data Base will be indexed and served by Wide-Area Information Service (WAIS) software; a WAIS server will be installed on one of the Laboratory's workstations. Most of the WAIS implementation in the Laboratory in FY 1993 was done by S. Brockman.

Central U.S.-- During FY 1993, numerous geological and geophysical digital spatial data sets supplemented base data layers for ten 30- by 60-minute (1:100,000-scale) topographic quadrangles encompassing the New Madrid seismic zone. The base layers are hydrography, roads and trails, railroads, airports, pipelines, and power transmission lines. The thematic data layers include two instrumental earthquake catalogs, shallow reflection and Vibroseis shot lines, aeromagnetic and gravity anomalies, magnetotelluric profiles, seismic velocity, radon emanation, and various topographic and seismotectonic features. The source data for the new thematic data layers were provided by A. Crone, R. Dart, T. Hildenbrand, S. Rhea, D. Stanley, and R. Wheeler. Data layers portraying infrastructure elements at risk in the Central U.S. were generated by R. Wheeler and S. Rhea. These data included alignments of oil, gas, and petroleum products pipelines, railroads, limited access highways, large dams, and nuclear facilities. Liquefaction potential, essential facilities data sets (schools, hospitals, firestations, and bridges), and settlement potential data of Shelby County, Tennessee were provided by H. Hwang and T.-S. Chang, both of Memphis State University. Data from the 1990 decennial Census of Shelby County were obtained from the Bureau of the Census to provide information on the residential housing stock in the County. All of the new data sets were added to the Geologic Hazards Data Base.

Numerous maps and illustrations were produced in the Laboratory for use by various workers. Notable among these were a final multi-sheet seismotectonic map (MF-Map series) of the New Madrid region and three-sheet map of infrastructure elements at risk prepared by R. Wheeler and S. Rhea for a chapter in a USGS Professional Paper. The seismotectonic map will show new geologic and geophysical information collected in the decade and a half since the previous seismotectonic map of the area. The Professional Paper chapter describes the data sets, notes spatial relations among them, and suggests likely social and economic impacts of a large New Madrid earthquake. Other maps of interest were of Shelby County, Tennessee and Memphis at 1:100,000 scale that portray soil profiles, liquefaction susceptibility, and infrastructure; the maps were prepared by A. C. Tarr in collaboration with H. H. M. Hwang and T.-S. Chang of Memphis State University. Three preliminary maps characterizing the residential housing stock of Shelby County, at the census block group level, were produced: age of dwelling; population density per dwelling; aggregate value of owned and mortgaged housing.
A handsome color USGS map poster portraying the seismicity of the New Madrid seismic zone draped on mosaic of 19 Landsat scenes was printed and released during the Fiscal Year (U.S. Geological Survey, 1993). J. Michael was responsible for graphic design and details of map production before the map was printed. The map has been widely distributed as a USGS outreach product.

A catalog consisting of tabular listings of archived Central U.S. ARC/INFO data sets and graphics depicting each data layer was published (Tarr, 1993a). The resultant catalog proved to be a useful outreach product for distribution to USGS-supported projects.

Pacific Northwest -- During FY 1993, new thematic data supplemented digital data base layers for three 30- by 60-minute (1:100,000-scale) topographic quadrangles encompassing the southern Puget Sound; these new data sets were contributed by G. Raines (WMR, Reno) and Water Resources Division personnel in Tacoma, Washington and added to the Geologic Hazards Data Base. These data included the geologic map of Oregon and contours of sediment thickness and a DEM for the entire Puget lowland. Numerous illustrations, poster graphics, and maps were prepared by J. Michael for R. Bucknam, S. Personius, and T. Pratt using data from the Geologic Hazards Data Base.

Colorado Geologic Hazards -- Data sets pertinent to the needs of Earthquake Hazards Reduction and Landslide Hazards programs, in cooperation with the Colorado Natural Hazards Mitigation Council, were added to the Geologic Hazards Data Base during FY 1993. These data included base data layers for selected areas of the Front Range and Western Slope, the geologic map of Colorado and several 1:100,000 quadrangle maps in the Rockies, and digital topographic contour data for the Slumgullion debris flow near Lake City, Colorado. A series of digital Soil Conservation Service STATSCO soils series maps for Colorado were assembled using ARC/INFO. J. Michael used these Colorado digital soils data to prepare color eolian soils maps of eastern Colorado that are used by R. Madole in his arid lands research for the Global Change and Climate History Program.

California -- The Laboratory provided A. Frankel with a gridded version of the ARC/INFO geologic map of the San Francisco Bay area obtained from C. Wentworth, WRG, Menlo Park. The geologic units of the original map were aggregated and then gridded. Frankel used the geology grid to modify a bedrock ground acceleration map and later will use the grid to help model the effects of the sedimentary basin. A similar gridded data set of the San Bernardino area was prepared for Frankel.

Quaternary Fault Map of North America-- The Computer Graphics Laboratory assisted in providing facilities, consultation, and cartographic services for acquisition of digital fault data for this new project under the direction of M. Machette. Most of the compilation and digitization of faults in western States has been completed and presented as maps to an international team of collaborators.
The most challenging task thus far was attributing a scanned version of the complex California State fault map. The completed digital fault data sets are expected to be extremely useful to numerous other projects.

Laboratory Expansion -- The number of projects requesting services from the Computer Graphics Laboratory increased substantially during the fiscal year, resulting in contention for the available hardware and software resources in the Laboratory. At the beginning of FY 1993, Laboratory computer resources consisted of two Sun Microsystems 4/75GX workstations, 6.3 GB hard disk on-line storage, two single-seat (Rev. 6.0) ARC/INFO license and one three-seat node-locked (Rev. 5.0.1) license, an Exabyte 8mm tape drive for data base backups and data exchange, a Tektronix 4207 terminal, and an Altek AC40 digitizing tablet (36" by 48"). By the end of FY 1993, all ARC/INFO licenses had been converted to Rev. 6.1.1 operating on SunOS v. 4.1.3 and OpenWindows 3; the node-locked license now uses one of the workstations as a server. A Tektronix XP356 X-terminal was purchased and 4 GB of hard disk on-line storage were added.

Reports Published


LOCAL GOVERNMENT USE OF EARTHQUAKE HAZARDS INFORMATION—
ASSESSMENT OF PRACTICE IN THE SAN FRANCISCO BAY REGION

Award Number: 14-08-0001-G2130
Program Element IV.2
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INVESTIGATIONS UNDERTAKEN

A project team consisting of the principal investigators assisted by Associate Planner, Laurie
Johnson carried out this study which has two basic objectives:

1) To determine how local governments in the San Francisco Bay Region are using EHI,
particularly that provided by USGS.

2) To explore how the content, format, and transfer of EHI might be modified to foster more
effective use.

These objectives have been met by interviewing local officials in the San Francisco Bay Region
and analyzing the results. We developed lists of USGS maps and reports addressing
earthquake hazards for each of the nine Bay Area counties plus Santa Cruz County. We ended
up with a one page list of products covering the Bay Region and another page for each county
listing products covering all or part of the county. The product lists were incorporated into an
interview guide which was used as the basis for discussions with local staff members about
their use of EHI.

The next step was to select jurisdictions to interview. We planned to conduct up to thirty
interviews including all the San Francisco Bay Area counties, at least one city in each county
and regional agencies with a land use planning function. As the interviews proceeded, it
became clear that consultants play a crucial role in the local use of EHI and we added several
consulting firms to the interview list. Table 1 lists the 30 agencies interviewed.

Table 1. AGENCIES INTERVIEWED BY TYPE OF AGENCY

<table>
<thead>
<tr>
<th>Cities (10)</th>
<th>Counties (8*)</th>
<th>Regional Agencies (7)</th>
<th>Consultants (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairfield</td>
<td>Alameda</td>
<td>Association of Bay Area Governments</td>
<td>Blayney Dyett</td>
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<tr>
<td>Healdsburg</td>
<td>Contra Costa</td>
<td>San Francisco Bay Conservation and Development Commission</td>
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<td>Napa</td>
<td>Marin</td>
<td></td>
<td>William Cotton Associates</td>
</tr>
<tr>
<td>Pacifica</td>
<td>Napa</td>
<td>Delta Protection Commission</td>
<td>William Lettis Associates</td>
</tr>
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<td>Pleasanton</td>
<td>San Mateo</td>
<td>East Bay Municipal Utilities District</td>
<td>(geotechnical)</td>
</tr>
<tr>
<td>San Francisco</td>
<td>Santa Clara</td>
<td>Metropolitan Transportation Commission</td>
<td>LSA Associates</td>
</tr>
<tr>
<td>San Jose</td>
<td>Santa Cruz</td>
<td>Governor's Office of Emergency</td>
<td>(environmental)</td>
</tr>
<tr>
<td>San Ramon</td>
<td>Sonoma</td>
<td>Services/Bay Area Regional Earthquake</td>
<td>Darwin Myer Associates</td>
</tr>
<tr>
<td>Santa Cruz</td>
<td></td>
<td>Preparedness Program*</td>
<td>(geotechnical)</td>
</tr>
</tbody>
</table>

* San Francisco is both a city and a county. It is listed as a city here. Solano County Planning
  Department staff declined to participate in an interview.

** These are state agencies with specific regional programs or responsibilities.
We selected the interview sites to include cities with a variety of terrain--hillsides, baylands, valleys, coasts--and at various stages of development, ranging from built out (San Francisco) to rapidly growing (Fairfield). We also looked for different population sizes, large and small planning staffs, and different earthquake hazards and land use issues. In 1990, the cities range in size from Healdsburg with fewer than 10,000 people to San Jose with over 3/4 million.

**Interviews**

In all the local jurisdictions, we contacted the planning departments to set up the interviews. We explained the purpose of the study and asked help in assembling the appropriate staff members to interview. We interviewed 56 people in the 30 agencies as shown in Table 2. Thirty-four were planners or working in a planning position (an agency administrator is counted as a planner). Seven were civil engineers from public works or building departments (one non-engineer building inspector is counted as an engineer), and fourteen were geologists or geotechnical engineers. Two of the planners had some education in geology and one geologist was working primarily as a planner. In every jurisdiction with a staff geologist, that person took part in the interview.

Table 2. **INTERVIEWEES BY PROFESSION AND TYPE OF AGENCY**

<table>
<thead>
<tr>
<th>Agency</th>
<th>Planners</th>
<th>Engineers</th>
<th>Geologists</th>
<th>Totals</th>
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<tr>
<td>City</td>
<td>15</td>
<td>4</td>
<td>1</td>
<td>20</td>
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<tr>
<td>County</td>
<td>13</td>
<td>3</td>
<td>3</td>
<td>18</td>
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<td>Regional</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Consulting</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Totals</td>
<td>34</td>
<td>8</td>
<td>14</td>
<td>56</td>
</tr>
</tbody>
</table>

All the city and county interviews and most of the consultant interviews were conducted on-site by a two person interview team. The regional agency interviews and two of the consultant interviews were conducted by telephone. A copy of the interview guide was sent in advance of each interview. The on-site interviews were tape-recorded. After the interviews, we wrote a summary of each interview. Drafts of the summaries were sent to all agencies for review and revised in response to comments received.

Interviewees were asked to fill out "Use of Products" worksheets included in the interview guide. These worksheets list all the USGS and other EHI we were able to identify for the county. Respondents were asked to identify the extent of use of each product (on a scale of 1 to 7) and, for products used, the general type of use--planning studies, plans, and policy implementation. Fourteen of the agencies (three cities, three counties, four regional agencies, and four consulting firms) completed the worksheets and these are included as part of the interview summaries for these agencies.

**RESULTS**

This study indicates that USGS is highly regarded as a source of information about earthquake hazards. The EHI produced by USGS for the region is generally considered accurate and authoritative. The findings and recommendations below are basically positive, reflecting growing interest in earthquake hazards and use of geologic information since the San Francisco Bay Region Study was started more than two decades ago. They point to some trends and
needs, but mostly to the desire for USGS to continue providing the region's basic geologic and seismic information.

**Findings**

**Background Information**

1. Cities and counties in the Bay Area are more likely to use geologic expertise now than they were 15 to 20 years ago when the SFBRS products were being released.

2. Local governments are moving slowly, but steadily, toward GIS and the capability to use digitized map information.

3. The Loma Prieta earthquake stimulated few local actions to reduce earthquake hazards other than actions to comply with the state URM law and improve emergency response capabilities.

4. The observation that geologic review procedures may have averted damage in the Loma Prieta earthquake, if verified, could enhance support for such programs.

**Extent of Use of EHI**

5. Maps associated with mandated local actions, like the Alquist Priolo Special Studies Zones maps, will be used by local governments over other information. If the Earthquake Hazard Maps to be prepared by CDMG are linked to mandated policies, they, too, will be the primary maps used by local governments.

6. Interpretive maps and reports going beyond hazard identification to estimates of probabilities and vulnerabilities are used more than most EHI by all categories of users interviewed.

7. Maps which are the only source of information needed by users will be used.

8. Non-technical reports treating subjects of general public interest are needed to convey information to the many users of EHI who are not earthquake specialists.

**EHI Used by Cities and Counties**

9. Although city staff do not make frequent direct use of USGS products, most are regularly using EHI maps prepared by CDMG or consultants which are based on USGS mapping.

10. Local government interest in using EHI is demonstrated by the large percentage of jurisdictions which have retained consultants or arranged with CDMG to prepare hazards maps. Once available, local hazards maps become the primary source of EHI used by staff.

11. The USGS products from SFBRS are fulfilling a major function in the region by providing basic geologic and seismic maps and reports which over the years have been translated by others into hazards maps to meet the needs of local governments.

**Use of EHI by Professions**

12. Staff geologists and consulting geologists serving local government are the primary users of USGS information.
13. Consultants play an important role in transferring and interpreting EHI for application by cities and counties. Consultants should be a target for USGS outreach efforts to improve effective use of EHI.

Applications of EHI
14. The use of EHI in the review of development projects has become part of normal practice in the San Francisco Bay Area. This "institutionalization" has occurred over the last 20 years.

15. One apparent result of the state requirement for safety elements has been to encourage local governments to invest in earthquake hazards mapping.

16. Given tight local government budgets, cities and, to some extent, counties are favoring applications, such as specific plans and project review in which the costs of acquiring EHI for development decisions can be passed on to developers.

Suggested Improvements
17. USGS maps and information are generally perceived as accurate. The agency is viewed as a reliable source on seismic issues. Many of the suggestions are simply asking USGS to do more of what it is already doing or has done in the past.

18. The most basic need is for up-to-date, clear, jurisdiction-specific information about maps and reports available from USGS.

19. Local governments need up-to-date topographic maps, basic geologic maps, and a set of geologic hazards maps. It is not important to the local jurisdictions whether this need is met by USGS or CDMG, but coordination makes sense.

20. Mapping at a scale of 1:24,000 would be acceptable for many local planning applications.

21. The work of staff geologists and consulting geologists serving local government is critical to successful local use of EHI. They look to USGS for information and professional guidance.

22. Local governments with staff geologists almost always have a system for filing geologic reports. The information is retrievable for use in future mapping. The potential exists for a two-way information exchange between USGS and local governments.

Recommendations

The recommendations are drawn from the findings listed above. They essentially say that USGS should continue doing what it has been doing with some improvements in coverage and outreach. The recommendations are listed in rough order of priority, although we consider all of them important.

1. **Outreach.** USGS needs an outreach program to let users know what products are available and how to apply them. The program should include the following features:
a) **Lists of products available for each county.** The list should include all maps, including topography, water resources, and other non-EHI products. Each citation should include the date of issue or latest revision, price, a clear, non-technical description of the map contents, jurisdictions or area covered, and intended use. The lists should explain how to order the products. An index map showing the coverage of each map would also be helpful.

b) **Local maps interpreted and explained.** When USGS releases a new map or report for part of the Bay Area, a USGS representative, preferably the author of the work, should present it to the affected jurisdictions, explaining how it was prepared and appropriate uses. Text describing possible applications with examples should be incorporated into the legend material on EHI maps intended for local use. It might be valuable to have a communications specialist review map texts before the maps are released.

c) **Periodic workshops or seminars.** These could be held at various locations in the Bay Area where USGS scientists can tell users about work completed or underway in the area. Users can ask questions, let the scientists know what their needs are and get help in applying the information.

d) **More public information publications** like the Sunday newspaper insert--*The Next Big Earthquake in the Bay Area May Come Sooner Than You Think.* Local government officials respond to issues important to their constituents. Efforts to increase general awareness of earthquake hazards can lead to enhanced local earthquake safety programs.

e) **Assistance to users in applying EHI.** Publications giving guidance in how to apply EHI, including examples of programs using EHI and model regulations are needed, particularly by local planners. Sometimes, the guidance can be provided as part of a map or report; other times a separate document may be appropriate.

f) **Recognition within USGS for scientists who engage in outreach efforts.** Not all scientists are going to be good communicators on a layman's level, but those who are and are willing to devote the time need to be encouraged.

2. **Updated Maps.** A program is needed to regularly update the basic maps, particularly topographic maps, for the region. Accurate basic maps are essential to preparing maps interpreting hazards. More than anything else, USGS is looked to by local governments for basic topographic and geologic information. This should be provided and updated as conditions change. Updates are particularly essential in areas undergoing or about to undergo urbanization.

3. **Earthquake Hazard Maps.** A set of earthquake hazard maps showing areas of potential liquefaction, landsliding, and enhanced ground shaking should be available for each county at a minimum scale of 1:24,000. The state hazard mapping program directs CDMG to prepare such maps, but the state fiscal crisis may mean a long wait before they are completed. USGS could explore a cooperative program with CDMG to assist.

4. **Coordination with CDMG.** Both USGS and CDMG provide EHI for local government use. Neither agency has the resources to meet all the local needs for EHI. Working together each agency can make the best use of its resources. Future basic and hazard mapping planned by
USGS for the region should be coordinated with the state-mandated, CDMG mapping program.

5. **Support for Staff Geologists and Geotechnical Consultants.** Most local governments use EHI with the help of geologists or geotechnical engineers on staff or consulting. The work of staff geologists and consulting geologists serving local government could be supported by USGS through programs to inform the public about the importance of using EHI and ways EHI can be applied. The geologists also need improved access to information from USGS. Specifically, USGS could take such actions as filling orders promptly, keeping publications in print, publishing without undue delays, and ensuring access to information such as well-water data, working maps, and open-file reports. USGS should encourage field scientists to contact local geologists in areas where the USGS scientists are working. In general, the goal of earthquake hazard reduction is well served by a cooperative relationship between USGS scientists and their fellow professionals working for public agencies.

6. **Digitized Maps.** USGS should continue to explore the potential for providing digitized map information in anticipation of the increasing ability of public agencies to use such information. Efforts for the region should be coordinated with CDMG and ABAG to foster compatibility in formats.

7. **Evaluations of Past Efforts.** Research is needed to evaluate the effectiveness of past efforts to mitigate earthquake hazards, transfer EHI to local planners, and map hazards for local use. The evaluations would be useful in developing new programs to produce and encourage the use of EHI. For example, the following studies would be useful:
   a) **Evaluating the effectiveness of geologic review procedures** drawing on the best information and judgments available about performance in earthquakes like Loma Prieta.
   b) **Evaluating the usefulness of the interpretive reports** with planning sections prepared under the SFBRS.
   c) **Evaluating the usefulness of the maps prepared for San Mateo County** on a pilot basis with a view to preparing similar maps for other counties.

**REPORTS**

A final project report on the first phase of the project was submitted to the U.S. Geological Survey in July 1993. The report is entitled, *Use of Earthquake Hazards Information--Assessment of Practice in the San Francisco Bay Region.* The report contains the findings and recommendations from the study and a summary of the interview results. Appendices to the report contain tables with the initial tabulation of data from the interviews, the interview guide, and summaries of all the interviews. For information about the availability of the full report, please contact:

USGS Office of Procurement and Contracts--MS 205C
12201 Sunrise Valley Drive
Reston, VA 22092

A circular based on the study and describing how local governments can effectively use geologic information in reviewing development projects will be released by the Survey in 1994.
IV

SEISMOTECTONIC MAPS OF THE CENTRAL U.S.

9950-14295

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Denver, CO 80225
(303) 273-8589; wheeler@gldvxa.cr.usgs.gov
Program Element IV.I

Investigations

Before FY 1993 we conducted this work under project 9950-04541 (A.C. Tarr, Computer Graphics Laboratory). We split off as a separate project for administrative convenience.

In FY 1993 we continued to compile and produce (1) a three-sheet infrastructure map of the central U.S. with accompanying text, and (2) a five-map folio of seismotectonic maps of the New Madrid, Missouri, area with accompanying texts. We continued to put the maps and associated digital data bases into the hands of the target audiences by showing the maps at scientific and natural-hazards meetings, distributing scores of draft copies, and disseminating parts of the data bases electronically on request.

Results

1. The central U.S. infrastructure map comprises three sheets and shows about the central third of the conterminous U.S. at a scale of 1:2,500,000. The map shows main regional lifelines, urban areas, selected critical structures, expected isoseismals from a hypothetical planning earthquake in the New Madrid seismic zone, epicenters of damaging historical earthquakes, and areas underlain by materials that might liquefy or amplify shaking. A 61-page text describes the data, notes spatial associations visible on the map, and suggests possible physical, economic, and social impacts of a large New Madrid shock. For example, a substantial part of the East's energy supplies moves through natural gas pipelines that cross or pass near the New Madrid seismic zone. Consuming regions in the upper Midwest and the Northeast have little storage capacity for natural gas, so seismic disruption of the pipelines could have impacts far from the area of physical damage. The map and text await Director's approval for publication as a Professional Paper chapter.

2. The folio of New Madrid seismotectonic maps comprises five two-color maps and shows, at a scale of 1:250,000, a 2° x 2° area that includes the main epicentral alignments detected by the Central Mississippi Valley seismic network. The maps
show seismicity and sand blows, large structures inferred from geophysical data, geophysical survey and modeling lines, structure of the Mississippi Valley graben, and surficial and hydrologic features. Accompanying texts of 12-27 pages each cite sources of the data, note spatial associations visible on the maps, and suggest possible causal explanations for some of the associations. All five maps have been reviewed and are being edited for publication in the MF map series.

3. Seismotectonic maps are most useful if all the information is on a single map sheet. The abundance of information available for the New Madrid map area precludes that. However, we have selected about half the data sets from the New Madrid seismotectonic maps and crammed them onto a full-color, single-sheet draft of an I-map that we hope to have in review by January, 1994.

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