UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Office of Earthquake Studies

SUMMARIES OF TECHNICAL REPORTS, VOLUME VII

Prepared by Participants in

NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM

DECEMBER 1978

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Compiled by

Wanda Seiders and Jean Thomson

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Earthquake Hazard Reduction Program

CALIFORNIA DIVISION OF MINES AND GEOLOGY

IN COOPERATION WITH THE COUNTY OF LOS ANGELES

EARTHQUAKE HAZARDS GEOLOGIC MAPPING OF THE SAN ANDREAS FAULT ZONE, LOS ANGELES COUNTY, CALIFORNIA, NEAR VALYERMO, LAKE HUGHES, THREE POINTS, AND QUAIL LAKE

by Allan G. Barrows, David J. Beeby and James E. Kahle

U S G S GRANT NO. 14-08-0001-G-504

SUMMARY REPORT COVERING PERIOD JANUARY 27, 1978 to JULY 27, 1978

Detailed geologic maps are being produced for several segments totaling approximately 32 km of the San Andreas fault zone in Los Angeles County. The current geologic mapping of the Valyermo, Lake Hughes, east-half Quail Lake and west-half Three Points segments is a continuation of an overall Division program to map fault traces and the geology along the 124 km stretch of the San Andreas fault within Los Angeles County that has been cooperatively funded by the Division of Mines and Geology, Los Angeles County, and the U.S. Geological Survey.

The geologic maps in preparation upon 1:12,000 orthophoto bases are intended to supplement the annotated fault maps produced last year for these segments (except Three Points). Emphasis is upon geologic data that permit resolving ambiguities in the existence of faults inferred solely from geomorphic features. Study of the Quaternary alluvial deposits, locally varied and abundant, also permits interpretation of the recency of activity along many individual fault strands within the segments.

The Valyermo segment extends for 11 km along the San Andreas fault about 30 km southeast of Palmdale. Geologic mapping is essentially complete for the uplifted area of gneissic quartz diorite and Tertiary sedimentary rocks south of the San Andreas fault. Many faults within the pre-Quaternary terrane have been added to the fault map. The contact between the sedimentary strata and basement rocks is, however, a depositional one that has been only locally faulted. It is not a major thrust fault as previously mapped.

North of the San Andreas fault a nearly continuous sequence of late Quaternary alluvial fans containing debris from transfault sources is being mapped in an attempt to determine the activity of several faults that disrupt one or more of these units.

The Lake Hughes segment extends for 10.3 km along the San Andreas fault zone approximately 30 km west of Palmdale. Geologically the area consists of three major, lithologically independent blocks separated by faults. The southern block is a pervasively sheared, deeply weathered complex of gneissic granitic rocks that range from weakly foliated to highly gneissic, and locally contain inclusions of marble. The northern block is an unsheared granodiotrite containing numerous aplitic dikes but no metamorphic inclusions. Local flat ridge tops on the northern block have been modified by cultivation, and do not represent a sedimentary cover or peneplain. Drainage patterns indicate that this block has recently been gently tilted to the north, presumably associated with activity on the San Andreas fault. The central block represents the westernmost exposures of the Tertiary Anaverde Formation. Steeply dipping arkosic strata in this block have been uplifted and faulted in a large pressure ridge between two active faults.

The east half of the Quail Lake segment and the adjoining west half of the Three Points segment (combined length 10 km) are being mapped concurrently. Early Quaternary units may be offset right laterally as much as 8-10 km. Inactive faults of a possible former San Andreas fault zone, about 1 km south of the present fault, juxtapose slices of granitic and Tertiary sedimentary rocks. Basement rocks have been thrust over this assemblage along a series of south-dipping faults which have displaced older alluvial terrace deposits. North of the San Andreas fault, Quaternary deposits (derived from rocks south of the fault) have partially buried a sequence of Tertiary volcanic and sedimentary rocks and have been offset right laterally.

Tectonic Framework San Francisco Bay Region
8-9540-01618

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Investigations

1. Analysis of the relation between aeromagnetic anomalies, geologic units, and epicenters in the southern San Francisco Bay region. Cooperative work with W. F. Hanna and W.H.K. Lee.

2. Continuation of bedrock geologic mapping along active faults in Santa Cruz, Alameda, Contra Costa, Monterey and San Benito Counties. Cooperative work with T. W. Dibblee, Jr.

3. Continuation of investigation of timing and amount of movement along the San Gregorio fault. Cooperative work with J. C. Clark.

4. Coordination of studies for seismic zonation in the southern San Francisco Bay region.

5. Preparation of field trip guide to Santa Cruz Mountains for GSA Cordilleran Section meeting. Cooperative work with J. C. Clark and W. O. Addicott.

6. Preparation of landslide workshop and environmental program at Circum-Pacific Energy and Mineral Resources Conference. Cooperative work with T. L. Wright, T. H. Nilsen, and W. J. Kockelman.

Results

1. Tertiary sedimentary rocks in the Point Reyes area north of San Francisco were compared by S. Graham and W. Dickinson with so-called similar sequences in the Santa Cruz Mountains to help formulate 115 km of strike-slip movement along the San Gregorio fault since the early Miocene. A preliminary examination of the Point Reyes sequence mapped by A. Galloway reveals significant discrepancies in the age and correlation of his geologic units. The Drakes Bay Formation of Galloway is probably correlative with the Purisima Formation of the Santa Cruz Mountains, not the Santa Cruz mudstone as reported by Galloway. The Monterey Shale of Galloway probably consists of two formations of considerably different age and lithology--a siliceous shale and chert formation of middle Miocene age that is correlative with the Monterey Shale in its type area, and a semi-siliceous mudstone of late Miocene age that is correlative with the Santa Cruz Mudstone. More work is needed to determine how or even whether these units have been separated by movement on the San Gregorio fault.

2. Eight reports on the state-of-the-art for seismic zonation of the San Francisco Bay region have been prepared for the Conference on Seismic Zonation to be held in San Francisco on November 28, 1978. Topics to be covered include neotectonic framework, ground motion, liquefaction, landslides, building damage, and use of seismic zonation maps by city, county and regional agencies.

3. Information on the state-of-the-art for coping with landslide and fault problems in seismic regions was provided to participants from 37 countries at the Circum-Pacific Energy and Mineral Resources Conference in Honolulu, August 1-4, 1978.

Reports

Dibblee, T. W., Jr., and Brabb, E. E., 1978, Preliminary geologic maps of the Chittenden, Los Gatos and Watsonville East quadrangles, California: U.S. Geological Survey open-file report 78-453.

Howard, K.A., and others, 1978, Preliminary map of young faults in the United States as a guide to possible fault activity: U.S. Geological Survey Miscellaneous Field Studies Map MF-916.

GEOMORPHIC TECTONIC ACTIVITY CLASSES OF THE SOUTH FRONT OF THE SAN GABRIEL MOUNTAINS, CALIFORNIA

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Contract # 14-08-0001-G-394. October 31, 1978

SUMMARY

A geomorphic tectonic analysis was made of 59 mountain fronts along the south sides of the San Gabriel and eastern Santa Susana mountains of southern California. Thrust faulting has created multiple topographic fronts and piedmont forelands along most of the ranges. Four landscape characteristics were used to assign classes of relative uplift of the mountain fronts during the late Quaternary: (1) the type of alluvial landform present (entrenched and unentrenched alluvial fans, stream channels and terraces, and pediments) (2) the sinuosity of the base of a mountain front, (3) the ratio of valley-floor width to the mean height of the divides for a reach upstream from a front, and (4) the relative degrees of erosion of triangular facets.

The three part classification of relative tectonic activity of mountain fronts that was used in the Mojave Desert was expanded to five classes. Class 1 (active) was subdivided into 1A (valleys cut in cohesive materials) and 1B (valleys cut in noncohesive materials). Class 2 of the previous format was subdivided into class 2 (moderate tectonic activity), class 3 (moderate to slight tectonic activity) and class 4 (slight tectonic activity). Classes 5A, 5B, and 5C (inactive) describe three types of pedimented terrains. There is minimal contradiction between the four landscape parameters used to evaluate relative tectonic uplift, and the means of the quantitative parameters for the different tectonic activity classes are statistically significant at better than the 0.95 level.

Most of the class 1 fronts are in the eastern and western quarters of the study area. Where multiple topographic fronts are present, the range bounding fronts appear to have undergone maximum uplift rates during the recent geologic past (in most, but not all cases). Fronts that are internal within the range may have lesser recent uplift rates but have greater magnitudes of late Quaternary uplift than the bounding fronts. Many internal fronts, such as those associated with parts of the Santa Susana and San Gabriel fault zones, are considered to be moderately active to active.

The middle half of the study area is characterized primarily by class 2 and class 3 fronts, but much of this part of the San Gabriel mountains is north of the Verdugo and Raymond Hill faults, which may be active. Three short class 1 fronts are present, and each of these east-west fronts is at the southernmost projection of a piedmont foreland. These loci of relatively greater tectonic activity may be the result of (1) interaction between the range-bounding faults and faults of the Los Angeles Basin, or (2) the configuration of thrust sheets that may focus tectonic stresses where the sheet projects farthest into the piedmont.

Quaternary Deposits and Tectonics of the Antelope Valley-Western Mojave Region, California

8-9940-02090

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Investigations

Work this semester was largely: 1) compilation of USDA soils maps of the Antelope Valley and Saugus-Newhall region of northern Los Angeles and southeastern Kern Counties, 2) field work to translate soils information into a 1:62,500 scale map of Quaternary deposits for this region (4,000 km^2), 3) acquisition of well logs and other data that give the textural character and thickness of Quaternary deposits in structural basins beneath Antelope Valley, 4) acquisition of geotechnical information about near surface materials from highway, bridge, and other engineering studies, 5) construction of programs to crunch the numbers collected into a data base that is suited to description of the Quaternary units and to seismic zonation of the region.

Strip-map studies of active structures in and around the Antelope Valley at 1:24,000 scale are nearly complete, and we are presently resolving the stratigraphy around these features into the Quaternary deposits maps to give a synopsis of deposition and coeval deformation in the region. Simple arrays of surveying monuments are being installed for posterity on active faults and folds. We do not as yet have this work sufficiently together to report results of consequence.

Reports

Burke, D. B., and Clark, M. M., in press, Late Quaternary activity along the Garlock fault at Koehn Lake, Fremont Valley, California (abs.): EOS, J. 59, v. 12.

Vertical Tectonics

8-9950-01484

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Investigations

1. Continued studies of historic crustal deformation based on repeated spirit levelings and both continuous and discontinuous sea-level measurements and their relations to the late Cenozoic tectonics of southern California.

2. Continued investigations of historic crustal deformation in selected parts of central and northern California, especially within the area extending northward from the 39th parallel to the Oregon border.

3. Completed development of a regional vertical data base designed to serve the needs of the Geologic, Water Resources, and Topographic Divisions of the Geological Survey.

4. Completed development of various applications programs designed to interface with the vertical data base now operating on the Multics computer.

5. Completed manuscript concerning analysis and interpretation of data regarding character, distribution, and rates of slip on the San Andreas fault in central California (in review).

Results

1. Rates of cumulative maximum uplift identified with the two recognized episodes of uplift and partial collapse, associated with the geodetically defined phenomenon now known as the southern California uplift, closely accord with those rates deduced from geologic considerations. Thus, the geodetically defined secular rates of maximum uplift of about 1 cm/yr are consistent with those developed from studies of marine terrace deformation along the south flank of the Transverse Ranges (Wehmiller and others, 1977). Similarly, maximum cumulative subsidence identified with the southern margin of the uplift is localized within the deep basinal part of the Salton Trough.

Comparisons between the two well-defined episodes of uplift and partial collapse indicate that the southern California uplift may be the product of decoupling and viscous flow beneath the seismogenic zone, presumably driven by continuing motion between the irregularly margined plates south of Maricopa. Because the magnitude of the maximum uplift associated with each event was roughly the same, there may be some threshold load above which collapse (viscous flow) may ensue; the absence of total collapse may be a function of precollapse strain hardening within the postulated subseismogenic viscoelastic layer.

2. Preliminary examination of the vertical control record in northern California suggests that the area east and north of Cape Mendocino may have sustained episodic uplift not unlike that recognized in southern California. The data are so limited, however, that coseismic and aseismic deformational events are not readily distinguished.

Reports

Williams, T., Johnston, M. J. S., Castle, R. O., and Wood, S. H., 1977, Local magnetic field measurements in southern California--comparisons with leveling data and moderate magnitude earthquakes [abs.]: EOS American Geophysical Union, Transactions, v. 58, no. 12, p. 1122.

Castle, R. O., 1978, Leveling surveys and the southern California uplift: U.S. Geological Survey Earthquake Information Bulletin, v. 10, no. 3, p. 88-92.

Quaternary Faulting in Southern California

8-9940-01293

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Investigations

1. Map and describe recently active trace of the Hilton Creek fault, Mono County, CA.

2. Place numerous, simple, cheap, monumented quadrilaterals across active faults of southern California in order to better measure future displacement.

3. Obtain cores from holes drilled by Conservation Division in certain playas of the California desert.

Results

1. The Hilton Creek fault is one of the main faults by which the eastern front of the Sierra Nevada steps westward from Owens Valley into the Mammoth embayment. It has the largest Holocene displacement measured so far along the eastern front of the Sierra Nevada (25 m, normal). The fault extends from its southern end in the Sierra Nevada near Rock Creek Lake NNW about 15 km to where it leaves the range front and splays about 10 km further into Long Valley caldera. Roy Bailey has mapped in detail the splayed part of the fault in the caldera; this investigation deals with the part in the Sierra Nevada.

Along much of its length in the Sierra Nevada the Hilton Creek fault follows the base of a steep bedrock scarp that locally is more than 1000 m high. Active slope processes and the steep scarp make most estimates of Holocene displacement fairly uncertain.

However, the fault also crosses the mouths of 3 glaciated valleys, where it vertically displaces deposits of the Tioga (latest Pleistocene) glaciation. Near Rock Creek Lake Tioga deposits are offset 1-2 m. About 3 km NW at Hilton Creek Lakes, the fault offsets Tioga deposits 1-7 m along a distance of more than 2 km. About 7 km further NW, the fault displaces Tioga lateral moraines of McGee Creek 25 m and Tioga/post-Tioga outwash of McGee Creek 17 m. The well-defined moraine crests of McGee Creek show no significant lateral displacement, which is consistent with the displacement of faulted moraines elsewhere along the eastern base of the Sierra Nevada. The increase of vertical displacement from Rock Creek Lake to McGee Creek is matched by an increase in overall height of the mountain front above the fault.

2. A program to festoon active faults of southern California with cheap,

permanent monuments got underway this summer with the placement of 15 quadrilaterals along the Garlock fault. The quadrilaterals are roughly 20 m square and span the recent trace at intervals of 10-15 km, except where alinement arrays already exist. Corners of the quadrilaterals are brass tablets on steel rods, which are set in concrete at or below ground surface. We will publish, but not publicize, locations and dimensions. The monuments are either hidden or buried, to thwart ORV vandals who infest much of this region. We intend to measure the quadrilaterals periodically (1-5 yr.); their primary use will be to measure faulting and creep. Future locations will include western Mojave Desert, San Andreas, San Jacinto, and Elsinore faults.

3. Late in July we discovered a Conservation Division program that was drilling one to four 500-ft. deep exploratory holes in playas of the California desert. More than 20 playas had already been drilled; only Deep Spring, Saline, Panamint, and Fremont Valley remained.

Conservation Division allowed us to take one continuous core from each playa if we paid the extra cost (they were not taking core), so we set up a program to obtain, describe, label and store 2½ in. diameter by 10-ft. long cores. We will take core to whatever depth we can afford. OEG and the climate program will pay for cores from the first three playas. We will get two cores from Koehn Lake (Fremont Valley), one from each side of the Garlock fault near our trench sites east of Saltdale.

All the cores may contain important information about late Quaternary history; those from Koehn Lake may show rates of fault offset.

Drilling was supposed to start in August. However, the drill rig was stuck (literally) in Utah and did not arrive in Deep Spring Valley until late October.

Reports

Burke, D. B. and Clark, M. M., 1978, Late Quaternary activity along the Garlock fault at Koehn Lake, Fremont Valley, California (Abs.): AGU, San Francisco, December 1978.

Holocene Behavior of the San Andreas Fault
San Juan Bautista To Point Arena, California

by

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N. Timothy Hall
Edward A. Hay

Foothill-De Anza Community College District
Los Altos Hills, California

August, 1978

SUMMARY

Following systematic study of all available pertinent historic information regarding the 1906 ruptures along the San Andreas fault in Northern California, review of all published maps showing the most likely positions of 1906 breaks, and preliminary analysis of aerial photographs of the entire length of the fault zone, we selected a number of sites to evaluate more thoroughly by ground reconnaissance.

Having completed our initial field work of the fault along the total length of the 1906 break, six (6) potential exploratory trenching sites have been selected (Figure 1). Technical criteria upon which site selections were made are placed into two categories: geological and logistical. The characteristics of the various technical criteria are outlined in Table 1 below:

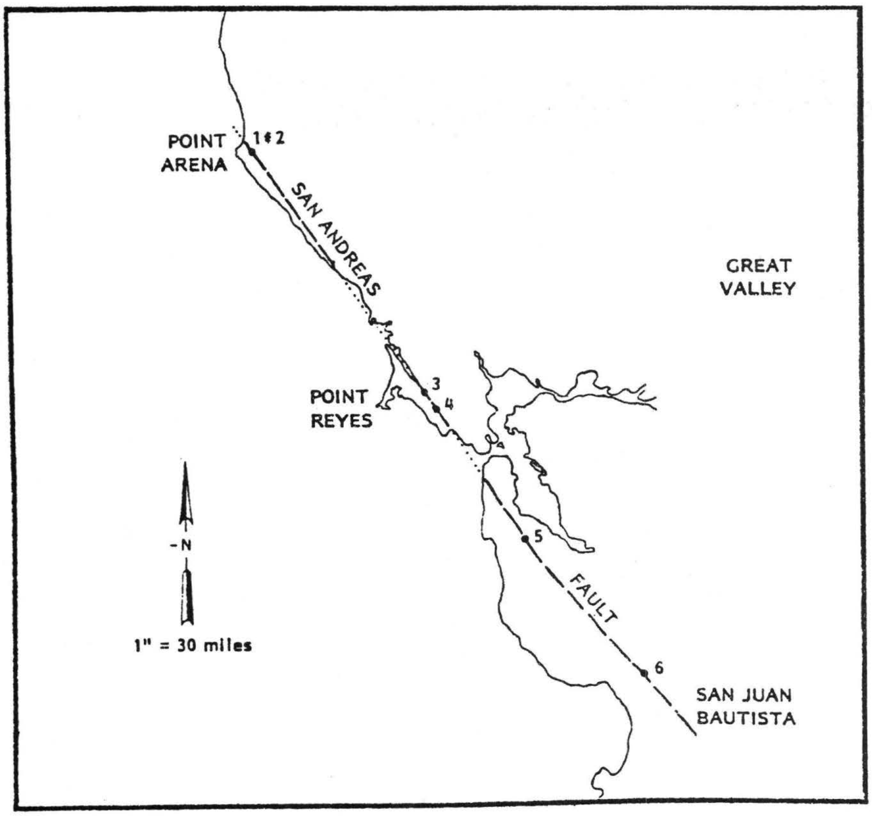

Figure 1. Location of six preliminary research areas along the 1906 trace of the San Andreas fau
Each area contains an exploratory trenchin
site which may be suitable for recurrence interval studies.

SITE NAMES

1 - Garcia River (Olsen Ranch)
2 - Garcia River (Jones Ranch)
3 - Vendanta Retreat
4 - Dogtown
5 - Portola V
6 - Anzar Rc

TABLE 1 - Technical criteria for selection of possible exploratory trench sites along the 1906 break of the San Andreas fault.

Geologic Criteria

1. Site located on a section of the fault where physiographic evidence suggests that all or most of the Holocene faulting has been narrowly concentrated (i.e. the region is not characterized by multiple, branching or subsidiary faults).

2. Site is locus of Holocene deposition where sediments accumulate rapidly enough to form a record between successive surface faulting events. (Ideal rates of sediment accumulation i.e. between 2 cm/1000 yrs and 20 cm/100 yrs, but actual rates probably cannot be determined until some radiocarbon dates have been generated.)

3. Stratigraphy of the upper 4 to 5 meters of the site characterized by multiple, distinct and laterally continuous sedimentary units containing a sufficient amount of carbonaceous debris suitable for radiocarbon dating.

4. Site has deep enough water table to permit exploratory trenching to approximately 5 meters (minimum depth approximately 2 meters).

5. Site has a well documented history of the location and amount of 1906 ground displacement.

Logistical Criteria

1. Site is accessible to backhoe and other equipment.

2. Access permission to investigate site can be secured from land owner.

The next phase of research will be concentrated on a detailed evaluation of the six possible exploratory trenchings sites. On the basis of the technical criteria outlined above each site will be further analyzed in order to judge which one has the highest research potential. It is expected that one or more sites will exhibit subsurface stratigraphy extending back 2,000 to 3,000 years B.P. with datable horizons that have been offset by multiple episodes of faulting. Careful logging of the trench walls coupled with radiocarbon data should provide us with sufficient information to judge the faults recurrence interval and the style and amount of movement for the 1906 event and those events that preceeded it.

To accomplish this phase of our research we plan to reevaluate each site through the use of sequential aerial photographs to determine if, indeed, the area is characterized by a single master trace of the San Andreas fault. Once convinced of the single strand nature of the fault, each site will be revisited and detailed surface maps (i.e. scale 1 to 500 and larger) will be prepared. These maps will show fault-related surface topography, ground water indicators, and cultural features which are pertinent to the individual trench site. Preliminary subsurface exploration of several of the potentially productive sites will be conducted using both hand auger drilling equipment and backhoe exploratory test pits. It is anticipated that sufficient data can be gathered through this preliminary phase of subsurface work to allow us to determine which of the six sites would be the most productive site for a more extensive investigation.

San Francisco Region Geophysics

8-9730-00363

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Investigations

1. Interpretation of aeromagnetic map of the north Bay Region (lat. 37°52'30"N to lat. 38°52'30"N) at a scale of 1:125,000. Supporting materials at the same scale from various sources include: gravity map, contoured at 2 mgal; geologic map; seismicity map.

2. Model studies of selected magnetic anomalies from the above data. Possible models for simulation of magnetic anomalies fall into three general classes: steeply-dipping dike-like masses with great vertical extent; models with varying magnetic properties; or configurations involving gently folded sheets with relatively minor interruptions by steeply-dipping faults.

3. Collection of a few magnetic profiles by truck-mounted magnetometer across puzzling aeromagnetic anomalies that are not clearly explained by the known geology.

Results

1. Using epicenter data provided for the north Bay Region by Shirley Marks of OES for the period January 1, 1975-May 12, 1977, David Jefferis has prepared an updated version of W.H.K. Lee's Bay Area seismicity map which covered the period 1969-1974. The new data add some 1500 events, the majority of which are located within the Geysers geothermal area.

2. The belts and areas of significant seismicity in general correlate with aeromagnetic highs which are believed to be caused by serpentinite masses.

3. Sepentinite masses tend to occur along certain of the major active or recently active faults such as the Rodgers Creek, Green Valley, Hayward, Concord, and Collayomi fault zones.

SEMI-ANNUAL TECHNICAL REPORT

GEOLOGIC INVESTIGATION OF RECENCY OF FAULT ACTIVITY BY SURFACE TRENCHING ON THE WHITTIER FAULT, CALIFORNIA

2 December 1978
Contract No. 14-08-0001-16821

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SUMMARY

Initial results of our field investigation of the Whittier fault in Bee Canyon, Yorba Linda, Orange County, California, indicate that alluvial and colluvial deposits are displaced by faulting. The Whittier fault should be considered active at this location. The trenches exposing this evidence of recency of movement are the last two of twenty-two trenches and numerous bulldozer excavations that were positioned in areas in accordance with mapping of the fault by prior investigators. Our mapping locates the main trace 100 to 200 feet further north of previously mapped traces and was mapped upslope of topographic features which were thought to be related directly to faulting.

Difficulty locating the fault resulted from exposure of numerous old and more recent landslides that presented pseudo fault features later determined to be slide related. By process of elimination and bracketing of stratigraphic markers the trenches exposing the fault were achieved and excavated to depths of 16 to 20 feet.

Excellent trench exposure of faulted bedrock formations substantiates that the Whittier fault is a right-reverse oblique slip fault. As much as 24 inches of reverse vertical separation in alluvium-colluvium has been exposed across a

faulted zone 30-35 feet wide. Horizontal and oblique slickensides have been observed within the underlying bedrock. Faulting within the colluvial-alluvial deposits extends to within 8-10 feet of the surface and has been observed within massive to poorly bedded, irregularly laminated, lenticular to discontinuous silts, clays, sands and minor gravels. Typically the fault breaks through the alluvium are not obvious and are marked only by consistent vertical separations of key marker beds. Generally, fault breaks in the bedrock can be traced upward through the surficial deposits for short distances before the breaks branch and appear to terminate.

Strata containing datable materials are scarce, however terrestrial gastropods have been collected from a depth of 16 feet and carbonaceous material will be collected from dark, organic rich strata within the upper levels of displaced alluvium. The faulted alluvial-colluvial deposits were observed 7 and 8 November 1978 and detailed logs are being prepared.

Difficult logging access has been encountered where groundwater is perched at the alluvial-bedrock contact. Pumping has been utilized to achieve access for logging. Deposits possess sufficient consolidation and shoring has been effective in preserving the trenches and preventing the occurrence of caving.

Detailed logging of the trenches described above is being accomplished by covering the trench. It has been determined that faint geologic structure within moist sediments is much more visible with a concentrated light source and almost impossible to see with direct or diffused sunlight. Mattock and rock picks cannot be used without obscuring the fine details of bedding and faulting. The trench wall has been prepared using ice picks and fine-head screwdrivers to prevent tool imprints on the face of the exposure.

Detailed logging is in progress and it is anticipated that research under this grant will be complete on schedule. We have been requested to recompact our dozer trenches and restore the site as completely as possible prior to land development. This was not originally anticipated as a condition to property access and was not included in our final proposal budget.

Shallow Geophysical Investigations

8-9940-01897

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Investigations

1. Seismic refraction profiles were made in Cholame Valley, along the San Andreas Fault zone near Cholame, California to obtain velocities and depths to bedrock near a strong motion station and to locate the site of a hole to be drilled and instrumented.

Results

1. The velocities of the alluvium ranged from 5500 feet per second to 6000 feet per second and the bedrock velocities ranged from 9500 feet per second to 11,000 feet per second.
2. The depth to bedrock ranged from 450 feet to 1000 feet.

Neotectonics of the San Francisco Bay Region, California

8-9540-01950

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Investigations

1. Geologic mapping (1:24,000-scale) of the San Joaquin fault zone, a late Quaternary-age fault zone along the west side of the northern San Joaquin Valley, California, was continued. Attention was focused on establishing the location, character, and recency of faulting along the zone between Ingomar and Orestimba Creek, south of Los Banos.

2. A detailed study was made of the extent and timing of late Quaternary thrust faulting along the west side of the northern Santa Clara Valley in San Jose, Los Gatos, Saratoga, Cupertino, and Los Altos. A 1:24,000-scale geologic strip map of the fault zone is being prepared.

3. An analysis of the neotectonic framework of central coastal California, summarizing the most recent geologic information on active faulting was completed. The magnitude and frequency of large earthquakes expectable in the San Francisco Bay region were estimated to assess the seismic shaking hazard for microzonation of the Bay area.

Results

1. The San Joaquin fault zone was mapped northward from Little Panoche Creek, south of Los Banos, to just north of Corral Hollow, near Vernalis. Late Pliocene-(?) and Pleistocene-age Tulare Formation gravels and late Pleistocene stream terraces end abruptly along the fault zone in a line of east-facing normal fault scarps alined with the escarpment bounding the east flank of the Diablo Range anticlinorium between Vernalis and Ingomar, and Orestimba and Little Panoche Creeks south of Los Banos. Between Ingomar and Orestimba Creek, Tulare Formation gravels and the intercalated Corcoran Clay Member (slightly older than 600,000 years) are offset and tilted eastward along an intervening zone of eastward-dipping reverse faults that strike southeastward from O'Neill Forebay to Orestimba Creek, closely parallel bedding in the underlying Great Valley sequence. A groundwater barrier in late Pleistocene alluvium along San Luis Creek is alined with the northern prolongation of one of the faults at O'Neill Forebay.

Uplift and arching of the Diablo Range along the San Joaquin fault zone began sometime in the last 600,000 years, well after the initial uplift and anticlinal folding of the Diablo Range in the Pliocene.

2. A zone of westward-dipping thrust faults at the west side of the northern Santa Clara Valley was traced northward from Guadalupe Creek in San Jose into the southern mapped end of the Monte Vista fault zone at Stevens Creek near Cupertino. The line of thrust faults are the apparent southern prolongation of the Monte Vista fault zone, a belt of imbricate thrust faults that extends northwestward from Stevens Creek through the Los Altos Hills to Los Trancos Creek, south of Palo Alto.

The thrust fault zone locally juxtaposes the Jurassic-Cretaceous-age Franciscan Assemblage and Monterey Shale (Miocene) atop the Pleistocene-age Santa Clara Formation, and throws the Santa Clara Formation across late Pleistocene alluvium. The latest episode of large displacement on the thrust fault zone apparently occurred before the deposition of the alluvium preserved in the second of three terraces that stand above the flood plains of streams on the west side of the Santa Clara Valley. The highest of the three late Pleistocene-age terraces is truncated in a line of east-facing cliffs along the fault zone at Los Gatos Creek in Los Gatos. The second and more recent first terrace are not evidently offset.

3. The San Francisco Bay region lies astride the San Andreas fault zone at its intersection with two other major fault systems, the San Gregorio-Hosgri and the Hayward-Lake Mountain. "Basic" earthquake recurrence curves have been determined for earthquakes of different magnitude at given points on the Hayward, Calaveras-Sunol, Calaveras-Paicines, and San Gregorio fault zones, and parts of the San Andreas for which average geologic slip rates can be approximated. The curves suggest that large earthquakes ($M \geq 7$) have a "basic" recurrence of tens to hundreds of years on the faults.

Estimates of the "most probable" earthquake magnitudes that can be expected along principal active faults in the San Francisco Bay area if one-half the total fault length ruptured imply that $M \geq 6$ earthquakes are credible on most.

Reports

Accepted for publication

Herd, D. G., 1978, An intracontinental plate boundary east of Cape Mendocino, California: Geology, v. 6, in press.

Herd, D. G., 1978, Neotectonic framework of central coastal California and its implications to microzonation of the San Francisco Bay region: Proceedings of the Second International Conference on Microzonation, San Francisco, California, November 26-December 1, 1978, in press.

Approved by the Director

Herd, D. G., The San Joaquin fault zone--Evidence for late Quaternary faulting along the west side of the northern San Joaquin Valley, California (abst.): Geological Society of America Abstracts with Programs, Cordilleran Section, 75th Annual Meeting, San Jose, California, April 9-11, 1979 (submitted for publication).

CALIFORNIA DIVISION OF MINES AND GEOLOGY (CDMG)
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EARTHQUAKE HAZARDS ASSOCIATED WITH FAULTS IN THE GREATER LOS ANGELES AREA, LOS ANGELES COUNTY, CALIFORNIA, including faults in the SANTA MONICA-RAYMOND HILL, VERDUGO-EAGLE ROCK, AND BENEDICT CANYON FAULT ZONES

Summary Report - Grant No. 14-08-0001-G-510

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The study of the Santa Monica-Raymond Hill fault zone is nearing completion and final results will be included in the Annual Technical Report covering the period February 9, 1978 to February 8, 1979. During this reporting period investigations of local areas along the Santa Monica-Raymond Hill and Verdugo-Eagle Rock fault zones were conducted with the following results.

A comprehensive record of the geology along the Potrero Canyon fault in Pacific Palisades north of Santa Monica Bay has resulted from field work by CDMG and for the most part from previous work by John T. McGill, Geologist, U.S. Geological Survey, Denver, Colorado (1978, personal communication) and a previous report (unpublished) by Harry R. Johnson (deceased) dated 1932. From this work the probable surface trace of the fault has been delineated a distance of about 6,000 feet through the residential area east of Potrero Canyon.

Additional field work is planned to determine if the Holocene soil developed on Late Pleistocene deposits covering the terrace platform east of Potrero Canyon has been disrupted by faulting.

A prominent topographic scarp in Late Pleistocene deposits is evident on early topographic maps (1900's) of the west Los Angeles area. The scarp has a maximum relief varying between 30 and 45 feet and is well defined in the vicinity of University High School. Tentatively, it is concluded that the scarp is associated with an east-northeasterly trending fault in the Santa Monica-Raymond Hill fault zone. The fault is defined in the subsurface from data from oil wells west of Beverly Hills.

Field work along the Eagle Rock fault along the southern front of the San Rafael Hills indicates that the western segment of the fault is a thrust fault dipping about 27° to 30° to the north, at least near the surface, which accounts for the arcuate shape of the mountain front.

Tectonics of Central and Northern California

8-9950-01290

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Investigations

1. Examined and sampled exposures of Cretaceous and Tertiary strata in northern California for paleomagnetic and paleontologic study, to provide constraints in the interpretation of regional paleotectonics.

2. Investigated ground cracks that developed in August 1978 during a swarm of earthquakes about 26 km east of Mount Shasta, California.

3. Continued study of relations between carbon-dioxide discharges and seismicity.

4. Compilation of geologic data with particular reference to the problem of intraplate seismicity.

Results

1. Oriented samples of rock were collected at 16 scattered localities in the Coast Ranges and Klamath Mountains provinces. The samples are of sedimentary strata of Cretaceous and Tertiary age, and include both marine and continental facies. Paleomagnetic measurements are being made on the samples by E. A. Mankinen of the Branch of Petrophysics and Remote Sensing. The laboratory work is not completed, but preliminary results on some of the Cretaceous rocks suggest that there has been significant clockwise rotation of the Klamath terrane. The preliminary results are sufficiently encouraging to warrant more thorough sampling at certain localities.

2. The ground cracks 26 km east of Mount Shasta formed during a swarm of magnitude 4 (±) earthquakes, near the epicentral region. The cracks form discontinuous grabens along a north-trending linear structure for a length of more than a kilometer. Vertical displacement of 0.1 to 0.5 m is common. The cracks are thought by some investigators to result from movement along regional faults of tectonic origin, but they seem more likely to result from collapse of the roof of a lava tube.

3. The distribution of carbon-dioxide discharges generally follows the major zones of seismicity on both regional and global scales. Some carbon-dioxide discharges are emanations from the mantle, and some are from the metamorphism of marine carbonate-bearing sedimentary rocks. Carbon-dioxide discharges and seismicity are both effects of tectonic activity. The carbon-dioxide discharges are long-term phenomena, in comparison to the intermittent nature of earthquakes, and ultimately may be useful in the seismic hazard zoning of

intraplate regions where earthquakes are infrequent. The tectonic aspect of carbon-dioxide discharges has been studied in collaboration with Ivan Barnes of Water Resources Division and, during this report period, studies have been directed mainly toward a more complete documentation of the global distribution of carbon-dioxide discharges than was thought feasible in our initial report (see Barnes, Irwin, and White, 1978). Additional localities of carbon-dioxide discharges have been found in the field in northern California, and through literature search and correspondence.

Reports

Barnes, Ivan, Irwin, W. P., and White, D. E., 1978, Global distribution of carbon-dioxide discharges and major zones of seismicity: U.S. Geological Survey Water-Resources Investigations WRI 78-39, Open-file Report, 12 p., 1 map, scale 1:40,000,000.

Irwin, W. P., 197-, Tectonic accretion of the Klamath Mountain, in Ernst, Gary, ed., The geotectonic development of California (Rubey Colloquium Volume): University of California at Los Angeles, in press.

Lanphere, M. A., Blake, M. C., Jr., and Irwin, W. P., 1978, Early Cretaceous metamorphic age of the South Fork Mountain Schist in the northern Coast Ranges of California: American Journal of Science, v. 278, no. 6, p. 798-815.

PROJECT TITLE: Recency and Character of Faulting Offshore from Metropolitan San Diego, California
By M.P. Kennedy*, K.A. Bailey**, H.G. Greene** and S.H. Clarke**

CONTRACT NUMBER: 14-08-0001-16728

PRINCIPAL INVESTIGATOR: Michael P. Kennedy

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SUMMARY REPORT COVERING PERIOD OCTOBER 1, 1977 to SEPTEMBER 30, 1978

More than 2,000 km of continuous subbottom, high resolution, shallow penetration 3.5 kHz and medium resolution air gun reflection profiles indicate that the Rose Canyon fault zone offshore from La Jolla, California is a major Quaternary zone of deformation. It is composed of a highly complex series of principally west to northwest-trending en echelon faults that lie within three distinct subzones beneath 1) La Jolla Submarine Canyon 2) the area immediately adjacent to the coast north of La Jolla and 3) the area subparallel to the coast 10-16 km offshore. These subzones form the central, eastern and western parts of the Rose Canyon fault zone respectively.

The faults that underlie La Jolla Submarine Canyon trend more westerly than do the faults of the boundary zones northeast and southwest of it. They appear to be principally dip-slip in character, and together form a moderately symmetrical graben (La Jolla graben) about the canyon's axis. The La Jolla graben is a major structural low, one of a series of similar lows (such as San Diego Bay and Mission Bay) and alternating structural highs (such as Point Loma and Mount Soledad) along the Rose Canyon fault zone between Mexico and offshore La Jolla. These structurally positive and negative areas are considered to have resulted from compression and tension developed by strike-slip along the northwest-trending boundary faults of the zone.

Fault scarps and offset late Quaternary sediment associated with many faults within the Rose Canyon fault zone suggest that it is relatively young. Previous studies propose approximately 6 km of right separation on the Rose Canyon fault zone since the deposition of the late Pliocene San Diego Formation. These studies also suggest that 1 km of this movement has occurred since the deposition of the early Pleistocene Lindavista Formation. We suggest that Scripps Submarine Canyon once joined La Jolla Canyon at the position of an abrupt course change 2.5 km north of

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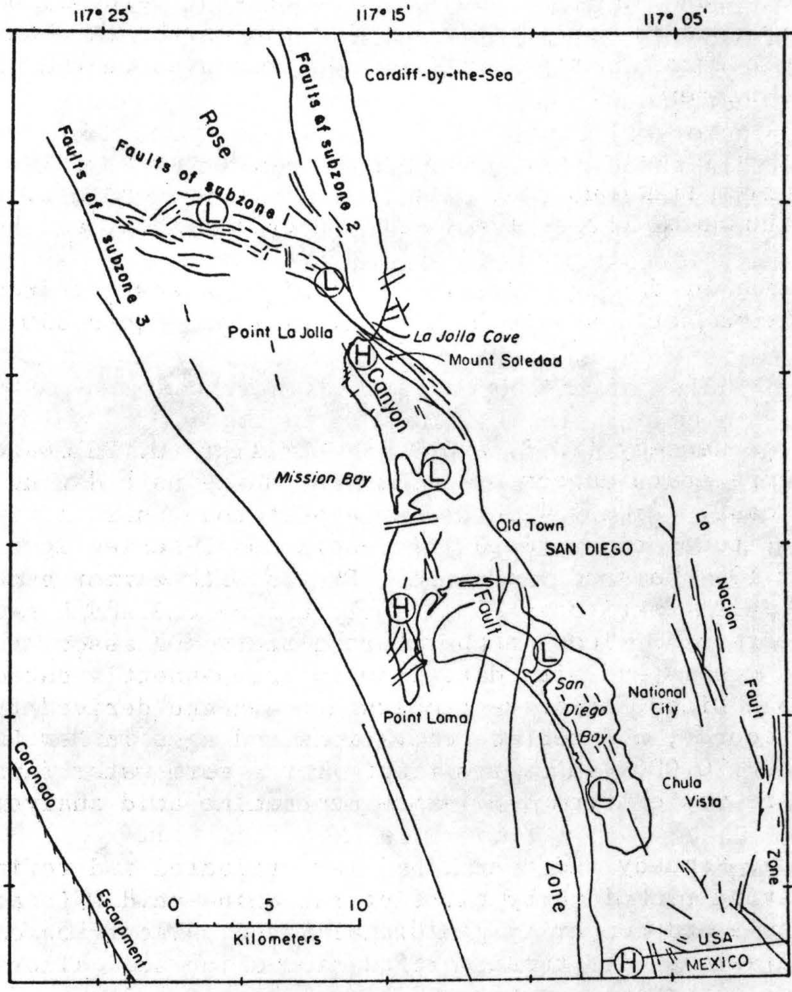
its present location and that subsequently it has been offset right laterally this amount along the eastern margin of the Rose Canyon fault zone. This offset must have, at least in part, preceded the deposition of the San Diego Formation.

Sediment cut by faults in the area has been divided into three informal units based on superposition and acoustic properties. The youngest of these is Holocene and late Pleistocene in age, has a velocity of 1.4-1.7 km/sec and is generally acoustically transparent. The intermediate age unit is an upper Tertiary-lower Quaternary succession, that has moderately strong reflection character, generally underlies a veneer of the acoustically transparent sediment and has a velocity of 1.7-1.9 km/sec. The oldest unit defined is Late Cretaceous and early Tertiary in age, has extremely strong reflection character, and velocities of 1.9-2.2 km/sec.



Map of the Rose Canyon fault zone between offshore Point La Jolla and Mexico (L) indicates structural lows within the fault zone and (H) indicates structural highs .

Coastal Tectonics, Western U.S.

8-9940-01623

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Investigations

1. The general objectives of the Coastal Tectonics project are to provide information on late Quaternary crustal deformation in the coastal region of the western U.S. The specific objectives are to assess tectonic state, date fault activity, establish recurrence intervals on faults and establish style and rates of crustal deformation. This information is used to assess seismic risk and earthquake hazards for populated regions and critical engineered structures in the coastal region of the western U.S.

2. Continuation of mapping and dating late Quaternary marine terraces and deposits from numerous coastal sites in the western U.S. with a focus on the Humboldt Basin, the Point Conception area, and Ventura.

3. Continuation of dating lacustrine deposits in western Great Basin to establish paleomagnetic and tephrachronology ties with coastal strata.

Results

1. With George Kennedy (USGS) and John Wehmiller (U. Delaware) refined the use of temperature aspect of molluscan faunas as a dating tool along the Pacific Coast. Faunas with cooler aspect than those living at equivalent latitudes today yield amino-acid and U-series ages estimates of 40, 85, or 105 thousand years old. Faunas with warmer aspect than those at equivalent latitudes today yield amino-acid and U-series ages of 120,000 years old. These temperature aspects and associated age estimates are consistent with data from an independently dated terrace sequence at San Diego, relative temperature and age derived from deep-sea isotope records, and terrace elevations and ages in New Guinea and Barbados. The 120,000 year age estimate for a warm-water fauna exposed near San Onofré was confirmed by subsequent amino-acid analysis.

2. With George Kennedy and John Wehmiller evaluated and refined the amino-acid dating technique by plotting raw amino-acid D/L ratios against latitude and comparing geologically and paleontologically derived correlations with those derived from amino-acid kinetic model ages. The agreement between the two approaches is quite good. The simple D/L vs latitude plots themselves provide rapid means of estimating ages.

3. With Sam Morrison (USGS) George Kennedy, and Andrei Sarna, refined late Quaternary stratigraphy in Humboldt Basin in Humbolt County, California to provide background information for reviewing geologic reports regarding seismic hazards in the vicinity of the Humboldt Bay nuclear power reactor. Microfossils, macrofossils and tephra provide a means of tentatively correlating tectonically deformed strata in the vicinity of the power plant with classic stratigraphic sequences exposed in the extreme southern part of the Basin.

4. With Gerald Weber (De Anza College) mapped faults in the sea cliffs near Pescadero in San Mateo County, California. Three marine terraces at 50m, 30m and 15m which were originally mapped as three separate surfaces with different ages are actually one terrace offset by a series of en echelon north-dipping, high-angle reverse faults. Bedrock (Pliocene Purisima formation) is thrust southward over deposits of this marine terrace along three fault traces. Total vertical displacement of the marine terrace platform is 30m, north side up. The age of the marine terrace is not known but is probably 100 to 300 thousand years old. The presence of major young faulting in this area supports the previous contention that a major branch of the Seal Cove-San Gregorio Fault intersects the coastline at the mouth of Pescadero Creek.

5. With George Cleveland (CDMG) and George Kennedy tentatively estimated the age of the first emergent terrace near Diablo Canyon, California to be 85,000 years old using the temperature aspect of the associated molluscan fauna.

6. Geologic studies by consultants revealed a faulted marine terrace at the proposed Cojo Canyon LNG site near Point Conception, California. Macro-fossil and amino-acid analyses place a tentative 85-125 thousand year age estimate on the faulted terrace. Our estimate that the youngest offset deposits are 5-8000 years old was confirmed by subsequent ^{14}C dating and soils stratigraphy by consulting geologists. A synclinal warp in the marine terrace conforms to a syncline mapped in underlying Miocene bedrock.

7. With Andrei Sarna (USGS), Bob Yerkes (USGS), and Steve Robinson (USGS) confirmed the 45,000 year amino-acid age estimate of a 150m-370m marine terrace near Sea Cliff in Ventura County, California. The tectonic uplift rate of this terrace suggests a Holocene age (<10,000 years) for the 15m terrace at the base of the sea cliff. ^{14}C dated molluscan fossils from the lower terrace are about 2,500 years old as predicted.

8. With Andrei Sarna and Bob Yerkes mapped extensive faulting of the 45,000 and 2,500 year-old terraces near Sea Cliff. The 45,000 year-old terrace, which runs along the westward plunging axis of the Ventura Avenue anticline, is offset by both north- and south-dipping high angle reverse faults on the limbs of the anticline. The Javon Canyon fault, which offsets the 45,000 year-old terrace about 40m, offsets alluvium graded to the 2,500 year-old terrace about 3.3m. Three, and possibly four, superposed colluvial debris aprons derived from collapse of the hanging wall of the fault interfinger with stream terrace alluvium and record three or four displacements over the past 2,500 years or less.

Reports

Wehmiller, J. F., Lajoie, K. R., Sarna-Wojcicki, A. M., Yerkes, R. F., Kennedy, G. L., Stephens, T. A., and Kohl, R. F., 1978, Amino-acid racemization dating of Quaternary mollusks Pacific Coast United States, in short papers of the 4th International Conference on Geochronology, Cosmochronology, and Isotope Geology: U.S. Geological Survey Open File Report 78-701, p. 445-448.

Wehmiller, J. F., Lajoie, K. R., Sarna-Wojcicki, A. M., and Yerkes, R. F., 1978, Unusually high rates of uplift in Ventura County, California inferred from Quaternary marine terrace chronology, Geological Society of America Abstracts with Programs, v. 10, no. 7, p. 513.

Earthquake Hazards Studies, Upper Santa Ana Valley and Adjacent Areas, Southern California

8-9540-01616

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Investigations

1. Completed mapping of the San Timeteo Badlands

2. Completed mapping of the Banning fault between Loma Linda and Whitewater Canyon

3. Continued study of the Quaternary Geology of the Upper Santa Ana Valley

4. Continued paleomagnetic and K-Ar dating of young basalts in the southern Mojave Desert

Results

1. Mapping of the Banning fault zone has led to the detection of a previously unrecognized young-appearing fault scarp in Quaternary alluvium near the east end of the zone and a series of northwest oriented scarps towards the west end. A segment of the Banning fault appears to be the disected sole of the landslide rather than a tectonic feature as previously mapped.

2. Mapping in the San Timeteo Badlands along the San Jacinto fault shows progressively greater displacements of progressively older sedimentary units with up to 25 km offset of Pliocene(?) units. Some 20 km north of the San Timeteo Badlands in the San Gabriel Mountains maximum displacement of basement rock contacts by the San Jacinto fault zone is only 15 km.

Reports

Cox, B. F., Paleoclimatic and tectonic significance of a Paleocene laterite and overlying debris-flow deposits on the north side of the Garlock fault in the El Paso Mountains, southern California: Geological Society of America Abstract.

Cox, B. F., and Morton, D. M., compilers, 1978, Generalized map of surficial materials in northwestern Riverside and southwestern San Bernardino Counties, California: U.S. Geological Survey Open-File Report 78-978, scale 1:125,000.

Cox, B. F., and Morton, D. M., compilers, 1978, Preliminary map of surficial materials in northwestern Riverside and southwestern San Bernardino Counties, California: U.S. Geological Survey Open-File Report 78-977, scale 1:48,000.

Miller, F. K., Morton, D. M., and Smith, C. C., (in press) photoreconnaissance maps showing young-looking fault features in the southern Mojave Desert, California: U.S. Geological Survey MF Map in press.

Morton, D. M., and Matti, J. C., Evidence for a vanished post-middle Miocene pre-late Pleistocene alluvial-fan complex in the northern Perris Block, southern California: Geological Society of America Abstract.

Morton, J. L., and Morton, D. M., K-Ar ages of Cenozoic volcanics along the Elsinore fault zone, southwestern Riverside county, California: Geological Society of America Abstract.

SUMMARY REPORT

INVESTIGATION OF THE HOSGRI FAULT OFFSHORE SOUTHERN CALIFORNIA, POINT SAL TO POINT CONCEPTION

by

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A seismic survey of the inner continental shelf between Point Sal and Point Conception has produced 425 km high-resolution SONIA, seismic-reflection profiles which document a sequence of well bedded, flat-lying, unlithified strata (acoustic stratigraphic Unit A) overlying a relatively flat erosion surface on highly deformed older strata (acoustic stratigraphic Unit B). Unit A is interpreted to represent sediment deposited on the beveled surface since the last lowstand of sea level about 17,000 to 20,000 years ago. Based on correlation with deep-penetration, seismic-reflection profiles and with other coastal geologic studies, Unit B is interpreted to represent late Tertiary sedimentary rock, predominantly of the Monterey, Sisquoc, and Foxen formations.

Both Units A and B are disrupted by faults and folds in the vicinity of the Hosgri fault which was projected from previous deep-penetration, seismic-reflection investigations. A zone of deformation up to about 2 km wide in Unit B and the overlying Unit A is mapped as the Hosgri fault zone. The disruption of Unit A indicates that the Hosgri fault has been active in post Wisconsin and probably Holocene time.

The zone of deformation mapped as the Hosgri fault zone continues from the northern part of the study area above the latitude of Point Sal southeasterly to about the latitude of Purisma Point where the Unit A sediment is too thick to be fully penetrated by the SONIA system. The trend of the fault at its southern end is aligned with faults and folds in the Point Arguello area seen on deep-penetration profiles. This southeasterly trend of the Hosgri fault, as well as the similar trend of other structures such as the Offshore Lompoc fault, appears to be toward the Point Arguello-Point Conception area suggesting that the offshore geologic structures of the study area merge with structures of the western Transverse Ranges.

Basement Tectonic Framework Studies, San Andreas Fault System

8-9950-01291

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Investigations

1. Field investigations in the basement terrane of the Breckenridge Mountain, Emerald Mountain, and Cross Mountain 15-minute quadrangles in the southern Sierra Nevada.

2. Reconnaissance in the Rand Mountains to examine the Rand Schist and the associated granitic terrane.

3. Further field examination of the coarse metamorphic and granitic clasts of the Temblor Range.

4. Reexamination of some of the metamorphic localities in the Point Reyes area and further sampling of the granitic terrane, including a rather coarsely porphyritic rock of possible correlative significance.

5. Thin-section petrographic study of granitic and metamorphic samples from oil-well cores in southeastern San Joaquin Valley.

6. Continuing petrographic study of granitic and metamorphic samples from the basement of the southernmost Sierra Nevada.

7. Preparation of road log and description of 26 selected granitic and metamorphic rock localities in the Santa Lucia and Gabilan Ranges of the Salinian block (a "self-guiding" tour of the basement that will be open filed).

Results

1. Completion of reconnaissance geologic mapping and sampling of the basement terrane of the southernmost Sierra Nevada north to 35°30' N. latitude (including the San Emigdio and Tehachapi Mountains) permits for the first time an integrated basement framework picture of the 3,900 km^2 (1,500 mi^2) area northeast of the San Andreas fault at its junction with the Garlock fault. This study involved reexamination, sampling, and, in some cases, remapping of basement rock units delineated over a long period of years in various degrees of detail by a number of workers. Only locally was the earlier work supported by petrographic and chemical data, which are being stressed in my current study. More than 35 granitic and metamorphic units have been identified and their patterns of distribution determined in this study. These units will provide excellent geologic clues in recognizing errant blocks and slivers that have been torn away from the south part of the Sierran basement block by

movements on the San Andreas and Garlock faults.

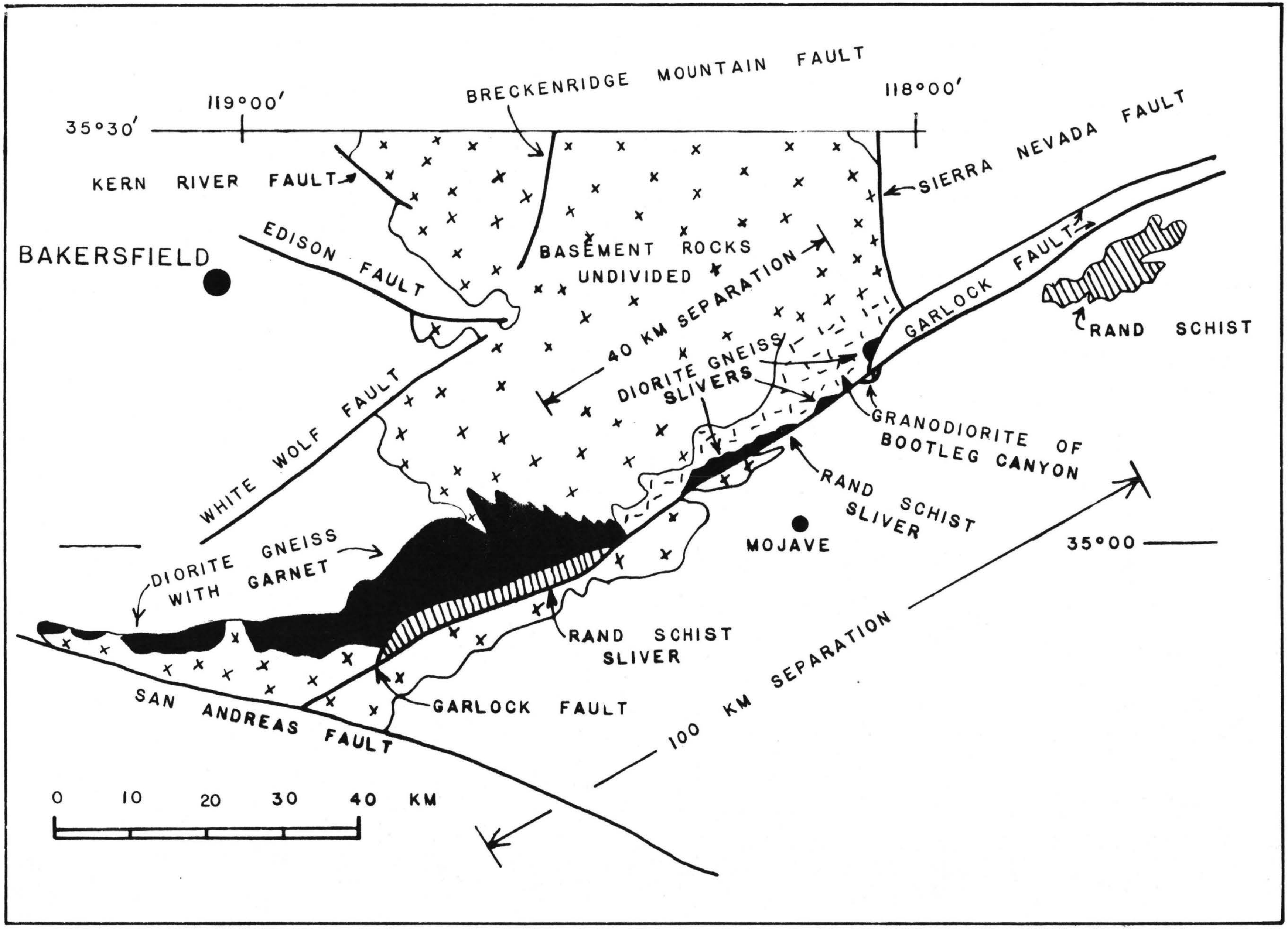
2. How basement framework studies can contribute to the solution of offset on major lateral faults is diagrammatically shown on the accompanying index map of the Garlock fault zone area. Isolated basement slivers whose source terrane has previously been unknown are strung out along this fault. Mapping of the current project has identified the rock types in these slivers and has tied them to their source terrane. For example, a 32-km (20-mi) long sliver of dark schist and quartzite in the Tehachapi Mountains can now rather confidently be correlated with the Rand Schist of the Rand Mountains. A newly discovered smaller sliver, some 4 km long (2.5 mi), of the same lithologies, north of Mojave, also in the Garlock fault zone, adds strength to the correlation. If this correlation is valid and the outcrops of the Rand Schist in the Rand Mountains extend no farther westward under the alluvium, the "smeared out" Rand Schist slices suggest a 100-km left-lateral separation along the Garlock fault zone.

Additionally a recently discovered (1978) sliver of dark hornblende-rich dioritic gneiss, which contains coarse haloed red garnets, extends the zone of garnetiferous diorite slivers from their known source terrane in the Tehachapi Mountains and records the "dropping off" of dioritic slivers to indicate a minimum offset of 40 km. Furthermore, the easternmost garnet-bearing sliver, newly discovered last month, indicates that significant lateral movement has taken place here on the northern branch of the Garlock fault (a branch that hugs the Sierra Nevada range front, whereas the line of most recent breakage cuts across the alluviated area to the south). This makes a blunt-ended sliver that looks analagous to the sliver occupied by Rand Schist farther west in the Garlock fault zone.

3. The granodiorite of Bootleg Canyon is an extensive granitic unit that is restricted to the northwest side of the Garlock fault in the Tehachapi Mountains; except as shown on the index map, where it occurs on both sides of the line of most recent Garlock fault movement. I interpret this outcrop to mean that the granodiorite south of the most recent trace is a sliver <u>in</u> the Garlock fault zone--analogous to the several fault slivers of granodiorite to the west along the fault zone.

<u>Reports</u>

Ross, D. C. and McCulloch, D. S., (in press), Cross section of the Southern Coast Ranges and San Joaquin Valley from offshore of Point Sur to Madera, California: Geological Society of America Map Series (contribution of the Plate Margins Working Group, U.S. Geodynamics Committee), scale 1:250,000.



Geology of the basement rocks north of the intersection of the San Andreas and Garlock faults.

Salton Trough Tectonics

8-9940-01292

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Investigations

1. Continuation of mapping of surface ruptures on the Imperial fault that accompanied the May 18, 1940 Imperial Valley earthquake.

2. Improvement of time constraints bearing on the estimation of the minimum average rate of slip on the San Jacinto fault zone since late Quaternary time.

3. Geologic and geochronologic study of pre-1940 movement on the Imperial fault at the International Boundary with Mexico.

Results

1. Low angle oblique aerial photographs of the 1940 surface rupture on the Imperial fault are available from the Imperial Irrigation District photo archives. Modern vertical aerial photographs of the area in Mexico traversed by the Imperial fault also have been obtained through the cooperation of the General Director of Attention and Prevention of Urban Emergencies of the Mexican Government. Using the photogrammetric technique of anharmonic ratios, fault trace data from the oblique airphotos have been projected on the modern vertical aerial photos. The results show for the first time in accurate map form the detailed trace of the 27 Kilometer-long segment of the 1940 surface break south of the International Boundary. Many photo linears located along the reconstructed fault trace suggest places where possibly undisturbed fault features might be found and studied to determine the age of pre-1940 faulting events.

2. Only a rough minimum estimate of the average rate of right-lateral slip on the San Jacinto fault zone through late Quaternary time has been made in the Peninsular Ranges of southern California. It is $\geq$ 2.6 mm/yr. The estimate is based on the position of gravel beds containing distinctive clasts that is displaced at least 5.2 Km from the site of the corresponding source terrane on the opposite side of the fault. The main difficulty in determining the rate of slip stems from uncertainty of the age of the displaced gravel beds. This minimum slip rate is computed from a possible age as great as 2 m.y. based on regional stratigraphic considerations.

Several rhyolitic ash beds stratigraphically underlie the gravel deposits, and the highest of these has been collected. The trace element chemistry of this ash bed has been analysed by A. M. Sarna-Wojcicki of the U. S. Geological Survey. According to its chemistry, this ash is correlative with the Bishop ash dated by the K-A method at its source in the Sierra Nevada at 0.73 m.y. This correlation places a substantially narrower time constraint on the age of the overlying offset gravel beds than was previously possible; it produces a new minimum estimate of the average slip rate on the San Jacinto fault zone of $\geq$ 7.1 mm/yr. for late Quaternary time. It must be emphasized here that this new estimate is still minimal because the geologic situation allows that the displacement of the gravel is underestimated and its true age is overestimated permitting a true slip rate several times greater than this minimum estimate.

The new minimum estimate has implications regarding activity and major earthquake recurrence alone the San Jacinto fault zone. Among other things it suggests that the Coyote Creek fault strand of the San Jacinto fault zone either may be younger than the main part of the zone or may be substantially less active than the main part, if the same age. The earthquake recurrence interval of about 200 years determined for the Coyote Creek fault partly from characteristics of the 1968 Borrego Mountain earthquake surface rupture may not be appropriate for the San Jacinto fault zone as a whole.

3. A trenching study of the Imperial fault at the International Boundary with Mexico has revealed evidence of pre-1940 structural disturbance of sandy beds which overlie a charcoal-rich silt layer. Charcoal collected from this stratum has now been dated at about 770 years B.P. The warped structure of this bed at the fault trace, when considered with the flat and unbent structure of an overlying sand unit which has been displaced by the fault only one time, during the 1940 earthquake, suggests at least one other but possibly several episodes of movement along the Imperial fault since 770 years B.P. Unfortunately, the stratigraphic features, as well as the physical limitations on how far the trenching could be extended, will not permit a more refined picture of the pre-1940 faulting history at that location.

LATE HOLOCENE BEHAVIOR OF THE SAN ANDREAS FAULT

U.S.G.S. Contract No. 14-08-0001-16774

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See page 380.

Late-Quaternary Seismicity and Rates of Tectonic Deformation, Panamint Valley, California

Roger S. U. Smith

University of Houston

Determination of tectonic rates in Panamint Valley constrains eastward tilting of Death Valley to a smaller rate than reported by Hooke (1972) or to an axis closer to Panamint Valley. East-west tilting in Panamint Valley is difficult to measure because the most prominent deformed features are north- to north-northwest-trending pluvial-lake shorelines. The Panamint Valley data can neither confirm nor deny Hooke's suggestion that tilting rates have increased exponentially with time in Death Valley.

The tectonics of Panamint Valley are consistent with tectonic models of northwest-southeast right-lateral shear distributed across the Basin-and-Range province. Rates of displacement seem comparable to those in a "typical" Basin-and-Range valley, Dixie Valley, Nevada, as described by Thompson and Burke (1973).

References Cited

Hooke, R. LeB., 1972, Geomorphic evidence for late-Wisconsin and Holocene tectonic deformation, Death Valley, California: Geol. Soc. America Bull., v. 83, p. 2073-98.

Thompson, G.A., and Burke, D.B., 1973, Rate and direction of spreading in Dixie Valley, Basin and Range province, Nevada: Geol. Soc. America Bull., v. 84, p. 627-32.

Quaternary Framework for Earthquake Studies
Los Angeles, California

8-9540-01611

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Investigations

1. Continued 1/24000 geomorphic/photogeologic/soil stratigraphic mapping of the coastal plain of Los Angeles County.

2. Continued preparation of preliminary surficial materials maps (scale at 1:125,000) of San Gabriel Valley, San Fernando Valley and Coastal Plain of Los Angeles County.

3. Selected 20 additional sites for <u>in-situ</u> measurements of shear-wave velocities employing down-hole techniques (J. Gibbs, Project Chief, T. Fumol, and J. Roth).

4. Selected 12 additional instrument stations in Los Angeles County at which to record ground motion generated by Nevada Test Site nuclear tests. (A. M. Rogers, Project Chief). Continued compiling geotechnical properties at instrument sites for entire L. A. Basin, Oxnard Plain and Upper Santa Ana Valley areas.

5. Completed small-scale liquefaction susceptibility map of parts of the San Fernando Valley, Los Angeles County, California.

6. Improved the data base for the 1:48,000 scale liquefaction susceptibility map of the San Fernando Valley.

7. With T. L. Youd, D. M. Perkins, R. J. Preston and E. J. King, completed small-scale (1:170,000±) liquefaction potential map of San Fernando Valley.

8. Selected 10 archeological sites from the voluminous ^{14}C compilation begun 1.5 years ago. These sites have potential for calibrating the regional soil stratigraphy in the Los Angeles basin. (C. Hastorf).

Results

Numbers correspond to items listed under investigations.

1. Mapping is 40% complete in Coastal Plain of L.A. County.

2. The preliminary surficial materials maps (scale 1:125,000) are being drafted; completion is imminent.

3. The addition of 20 new sites brings to 40 the number of sites selected for detailed downhole studies of shear-wave velocities. The result will be an improved data base for evaluation of ground response in terms of near-surface geology.

4. Compilation of geotechnical data for instrument stations recording NTS nuclear test ground motions is 75% complete.

5. 6. Identification of the youngest sediments occurring within what is generally a Holocene basinal setting in the San Fernando Valley rely on photogeologic comparisons using 1928 and 1938 (post-flood) photography, maps and field notes compiled by Los Angeles County Flood Control District during nine major flood-years between 1934 and 1956. Photogeologic features used to delineate areas of recent deposition or flooding include observed changes in patterns of distributary channels of alluvial fans, areas where row crops are washed out or are buried by sediment, parts of basins characterized by streams incised less than 1.5 meters and areas characterized by unvegetated bar-and swale channel deposits. Specifically excluded are areas of local ponding where culverts plugged and backed up. By identifying and delineating deposits which are less than a few hundred years old, the sediments most susceptible to liquefaction can be identified. Such youthful materials seldom have been buried deeply or for periods of time sufficient to result in greater degrees of compaction, a higher number of grain to grain contacts, greater opportunity for infiltration of voids with fines and chemical cementation, all of which tend to produce better cohesion and induration in a sediment with time.

7. A liquefaction potential map has been compiled for the San Fernando Valley, California. For a 46-year return period, the map shows areas where strong ground shaking is likely to produce liquefaction in sediments with high susceptibility. The map incorporates assessments of age and type of sedimentary deposits, ground water depth, and expected seismicity into the delineated zones. This map is useful to planners, building officials, engineers, and others responsible for minimizing seismic risk by pointing out areas where potential hazards exist and where further investigation, regulation, zoning, or other measures might be required. The map is not sufficient for evaluation of the actual liquefaction potential at an individual site. Site specific geotechnical investigations are required to make an assessment.

Reports

Youd, T. L., Tinsley, J. C., Perkins, D. M., King, E. J., and Preston, R. J., Liquefaction potential map for part of the San Fernando Valley, California. Submitted 1978/International Microzonation Conference Proceedings.

Semi-Annual Technical Report Summary
10 February 1978 to 10 August 1978

Compilation of Pre-1900 California Earthquake History
Contract No. 14-08-0001-G-513

Tousson Toppozada and Charles Real
California Division of Mines and Geology
1416 Ninth Street, Room 1341
Sacramento, California 95814
(916-322-9310) (916-322-9311)

Investigations

Historical literature is being searched to provide descriptive reports of 122 of the larger pre-1900 earthquakes within or affecting California. These reports are being used to produce estimates of epicenter location, local magnitude, and felt area for each event, thereby extending the California earthquake catalog back at least another century.

During the current grant year, preliminary isoseismal maps are being sketched for each event from felt reports in newspapers and other historical documents. These maps are being used to derive estimates of local magnitude and epicenter location. Sources being tapped for historical literature are the California State Library in Sacramento, the Bancroft Library in Berkeley, and the Huntington Library in Pasadena.

Results

The literature search for newspaper issues available at the State Library has been completed for the two decades 1880-1899. About 3300 newspaper issues covering this period have been examined of which about one-third have yielded earthquake reports.

Thus far, 42 earthquakes that occurred during the two decades 1880-1899 have been assigned preliminary source parameters based on intensity data interpreted from the felt reports (Table 1). The distribution of epicenters for the decades 1880-1899 respectively, is shown in Figures 1 and 2.

Anticipated products for the fiscal year 1978-79 are: 1) a catalog of all events researched that includes the estimated source parameters, 2) epicenter maps showing the locations of historical earthquakes and 3) a complete bibliography of references researched for each event.

Table 1. Chronological listing of historical earthquakes researched with assigned date and origin time, epicenter coordinates, local magnitude, felt area, and maximum reported intensity.

date Yr M D	time (GMT)	location lat(°N)	long(°W)	Max. Int. (MM)	total	areas (km^2) V	VI	VII	Mag.	Comments
1899/12/25	12:25	33.8	117.0	8		160000	20000	2600	6.3	San Jacinto
1899/10/13	5:00	38.4	122.7	6	1100				3.0	Santa Rosa
1899/7/22	20:32	34.3	117.4	7	165000	21000	3400		5.7	San Bernardino
1899/7/ 6	20:10	36.9	121.7	7	80000	18000	1800		5.6	Watsonville
1899/6/ 2	7:19	37.6	122.6	6-7	41000	5000			5.1	San Francisco
1899/4/30	22:41	36.9	121.7	7	56000	6900	860		5.3	Watsonville
1899/4/16	10:41	40.5	124.5	5	62000	8000			5.3	Eureka
1898/4/15	7:07	39.2	123.8	8		160000	12000	1700	6.3	Mendocino
1898/3/31	7:43	38.2	122.4	7-8	230000	41000	6700	920	6.1	Mare Island
1897/6/20	20:14	36.9	121.4	8	140000	44000	9400	800	6.0	Hollister
1896/8/17	11:30			5						Visalia, more information needed
1894/10/23	23:03	32.0	117.0	6	200000	100000	30000		6.3	Baja California
1894/7/30	5:12	34.5	117.5	5-6	125000	16000			5.7	Mojave Desert
1893/8/ 9	9:15	38.4	122.6	6-7	28000	2600			4.9	Santa Rosa
1893/6/30	13:30	38.1	122.5	5	13000	1000			4.3	Vallejo
1893/5/19	0:35	34.0	119.0	4-5	86000				5.5	Ventura
1893/4/ 4	19:40	34.4	118.5	7	80000	6000	500		5.3	San Fernando (Pico Canyon)
1892/11/13	12:45	36.8	121.5	6-7		10000	1000		5.2	Monterey Bay
1892/2/24	7:20	31.5	116.5	6+	1100000	250000	71000		7.0	Baja California
1891/10/12	6:28	38.3	122.3	7		18000	3500	300	5.6	Napa and Sonoma
1891/1/2	20:00	37.4	121.9	5-6	38000	7000			4.9	Lick Observatory

Table 1. (continued)

1890/8/23										Mono Lake, probably did not occur
1890/7/26	9:40	40.5	124.5	7	250000		6000		6.0	Petrolia
1890/4/24	11:36	36.9	121.6	8		26000	4900	830	6.0	Salinas
1890/2/ 9	12:06			5-6						Pomona, more information needed
1889/9/30	4:10	37.3	119.5	4-5	110000				6.0	Central Sierra Nevada
1889/8/28	2:15	34.1	117.7	5-6	40000	4600			4.9	Monrovia
1889/7/31	12:47	37.8	122.2	6	44000	3000			5.0	Oakland
1889/6/20	6:00	40.5	121.0	6+	110000				5.5	Lassen County
1889/5/19	11:10	38.1	121.8	7	59000	10000	980		5.3	Collinsville
1889/4/15	3:28	36.9	121.4	4	33000				5.0	Santa Cruz
1889/2/ 7	5:20	34.3	117.0	5+	45000				5.0	San Bernardino Mountains
1888/11/18	22:28	38.0	122.3	6	2700				3.5	San Pablo Bay
1888/9/17	11:51	37.2	121.7	6-7RF	15000				4.8	Lick Observatory
1888/4/29	4:48	39.3	120.9	6		14000	36000		5.5	Nevada City
1888/2/29	22:50	38.3	122.7	5	7900	300			4.0	Petaluma
1888/2/18	10:50			5						Point Arena, very small
1887/12/16	12:15			5						Point Arena, very small
1885/8/ 1	0:10			6						Cloverdale, very small
1885/4/12	4:05	36.3	120.9	6	320000	71000	12000		6.3	Central California
1885/4/ 2	15:25	36.8	121.5	5	120000	5500			5.5	Central California
1885/3/31	7:56	36.7	121.4	7	18000	1900			4.5	Mulberry
1885/1/31	4:45	40.3	120.6	7	120000	20000	2400		5.5	Honey Lake
1884/6/ 6	9:00									Red Bluff, very small

Table 1. (continued)

1884/3/26	0:40	36.9	122.1	6	80000	11000			5.5	Santa Cruz
1884/1/28	7:30			4						Humboldt County, very small
1883/10/22	14:00									Merced Falls, probably not an earthquake
1883/9/ 5	12:30	34.2	118.7	4+	27000	6400			5.0	Los Angeles
1883/3/30	15:45	36.9	121.6	7	81000	14000	4700	860	5.7	Hollister
1882/3/ 6	22:00	36.8	121.4	5	92000	7400	1260		5.3	Hollister
1881/4/10	10:00	37.6	121.3	5-6	210000	27000			6.0	East-central Coast Ranges

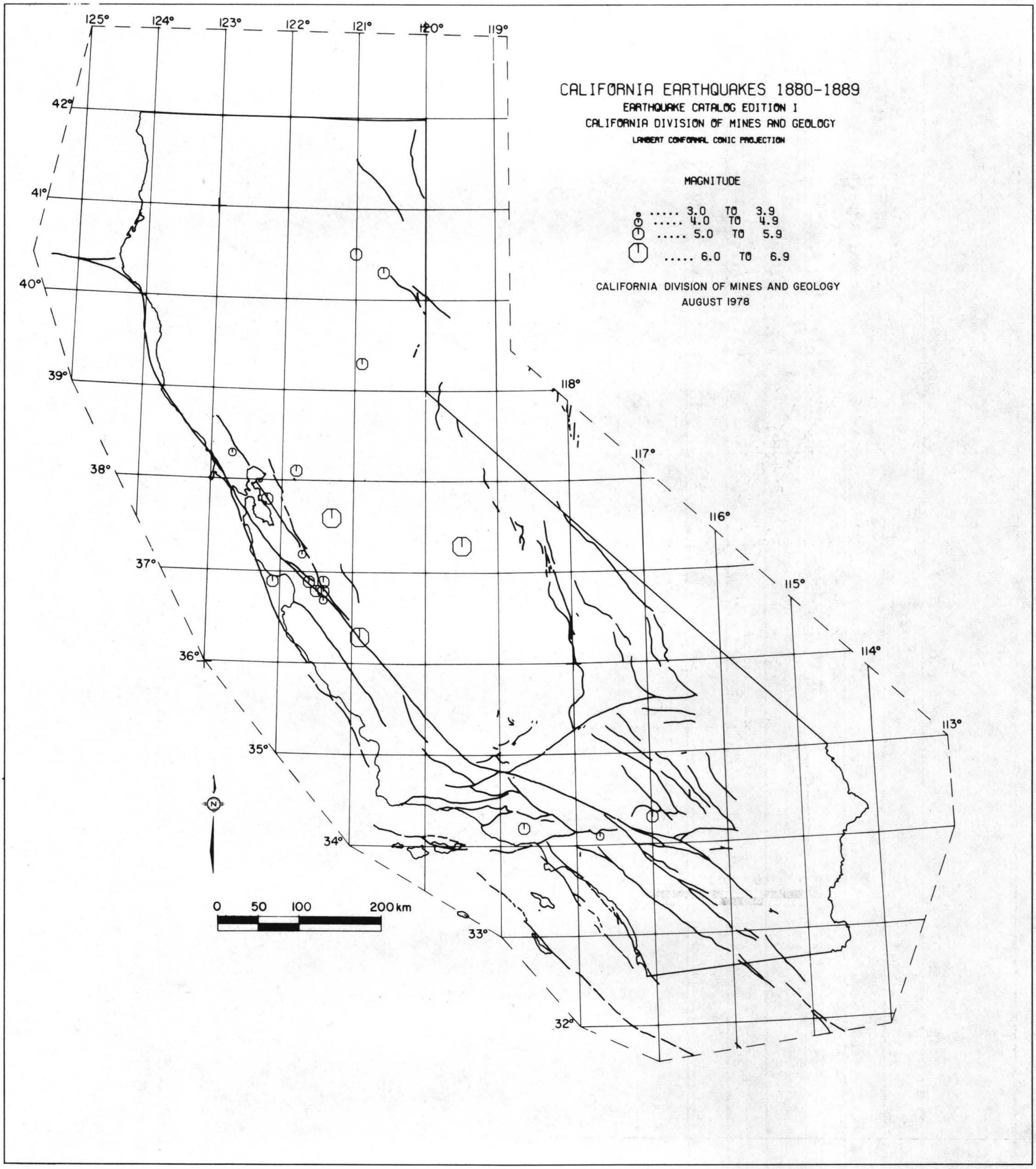
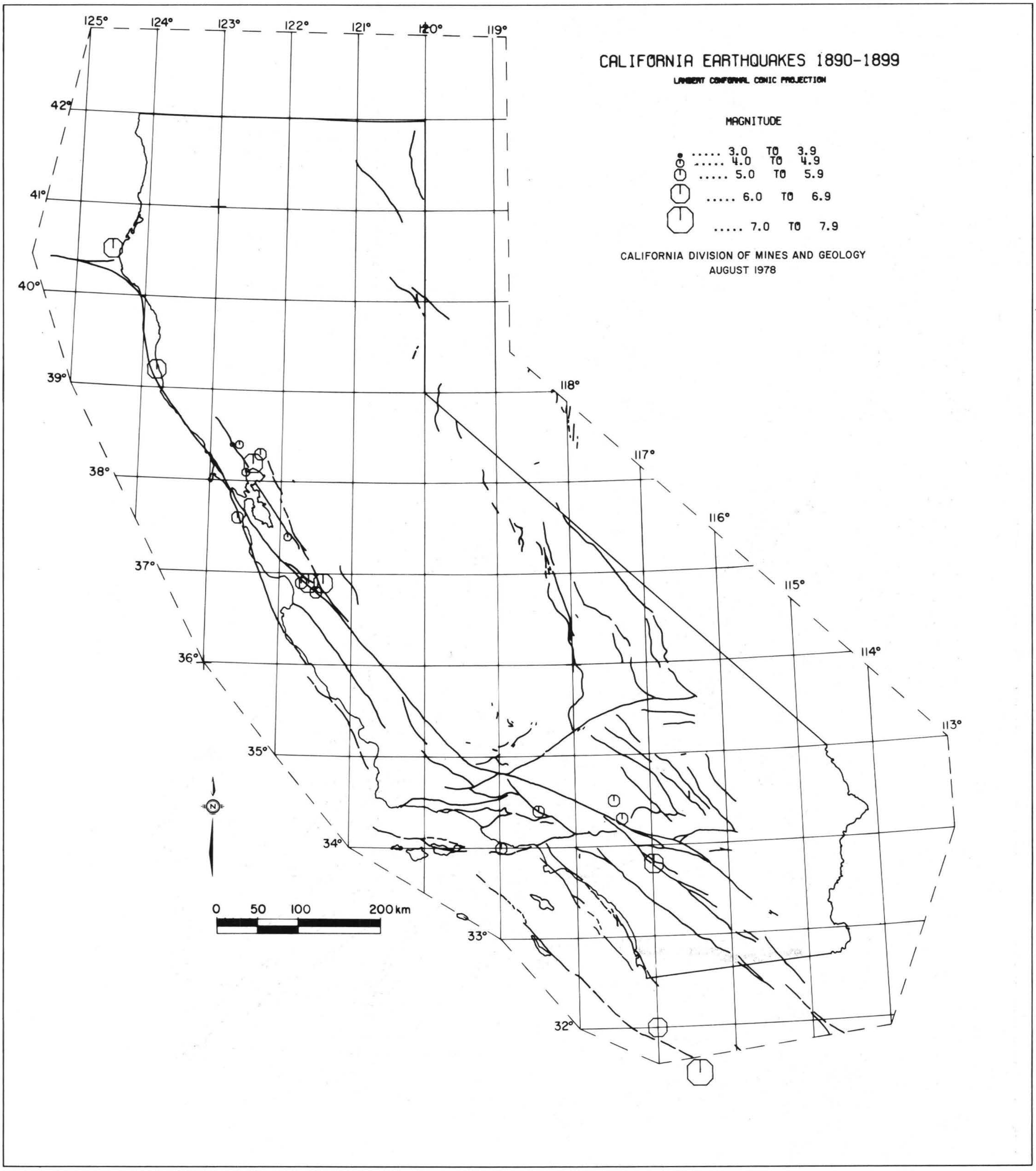

CALIFORNIA EARTHQUAKES 1880-1889
EARTHQUAKE CATALOG EDITION I
CALIFORNIA DIVISION OF MINES AND GEOLOGY
LAMBERT CONFORMAL CONIC PROJECTION
MAGNITUDE
..... 3.0 TO 3.9
..... 4.0 TO 4.9
..... 5.0 TO 5.9
..... 6.0 TO 6.9
CALIFORNIA DIVISION OF MINES AND GEOLOGY
AUGUST 1978
125° 124° 123° 122° 121° 120° 119° 118° 117° 116° 115° 114° 113°
42° 41° 40° 39° 38° 37° 36° 35° 34° 33° 32°
0 50 100 200 km
N

Figure 1


CALIFORNIA EARTHQUAKES 1890-1899
LAMBERT CONFORMAL CONIC PROJECTION
MAGNITUDE
..... 3.0 TO 3.9
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CALIFORNIA DIVISION OF MINES AND GEOLOGY
AUGUST 1978
125° 124° 123° 122° 121° 120° 119° 118° 117° 116° 115° 114° 113°
42° 41° 40° 39° 38° 37° 36° 35° 34° 33° 32°
0 50 100 200 km
N

Figure 2

SEMI-ANNUAL TECHNICAL REPORT AND SUMMARY

Investigation of Progressive Growth and Movements along branches of the Southern end of the Death Valley Fault Zone (A) and Investigation of Chronology and Time Relations Between Strike-slip and Normal Faulting, Recent Volcanism and Development of Fans in South-Central Death Valley, California (B)

8-9900-01268

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September 30, 1978

Part A: Southern end of Death Valley Fault Zone.

Summary of progress to date.

General. The general objectives of the work in this proposal are to extend southeastward detailed mapping already completed along the southern part of the Death Valley fault zone (Fig. 1). The mapping already done has yielded information that (1) an echelon branches of the fault zone are progressively younger towards the northeast side of the zone (2) some branches have younger movement along the northern part of the branches than on the southern part, (3) the floor of Death Valley along the youngest traces of the fault zone is folded into shallow basins and domes, (4) right lateral offset is as much as 10 miles for Tertiary sedimentary rocks and a few feet for active stream channels, and (5) traces of some fault branches die out in topographic highs that coincide with folds in the rocks. These observations suggest that the older branches of the fault zone are less likely to have movement along them than are the younger branches and that the northeast ends of the younger branches are most apt to be the loci for further movement.

Extension of mapping southeastward was proposed to further record interplay of movement along branches of the Death Valley fault zone and interplay of movement with branches of the Garlock fault zone. Mapping has been completed of about half of the proposal area of about 40 square miles at the expenditure of about half the time (Fig. 1). The mapping has been done on enlarged photographs and transferred to a clear sheet of mylar.

Rocks. Rocks in the fault zone in the mapped area include Precambrian gneiss; Precambrian diabase and sedimentary rocks of the Crystal Springs Formation, Kingston Peak Formation, Johnnie Formation; Mesozoic (?) granitic plutonic rocks; Tertiary volcanic and sedimentary rocks; and Quaternary Fan deposits. Assemblages of rocks tend to be constant between individual main branches of the fault zone. The principal rock south of the fault zone is Mesozoic diorite, which makes up the main mass of the Avawatz Mountains. The rocks immediately south of the southern branch of the fault zone commonly are made up of diorite beneath which is a complex mixture of fine-grained diorite, dikes of diorite aplite and pegmatite, and metasedimentary rocks.

The Precambrian sedimentary rocks exposed in the fault zone are similar to rocks exposed in the southern Salt Spring Hills (2-3 miles north of the fault zone) the Silurian Hills (about 5 miles east of the Avawatz Mountains), and in the crestal region of the Avawatz Mountains (about 3 miles south of the fault zone). The Precambrian sedimentary rocks in the fault zone become progressively more highly metamorphosed westward.

The Mesozoic plutonic rocks are granitic in composition and can be subdivided into three units based on megascopic observation. Dikes of granitic and basic composition are associated with the plutonic rocks exposed east, north, south, and northwest of the mapped area. They may be of some use in determining offsets along the faults.

The Tertiary rocks are abundant along the fault zones. The types include coarse monolithologic megabreccia, coarse fan gravel, conglomerate with coarse to medium sized clasts, sandstone, siltstone, gypsum, halite, celestite, and fine siltstone. They are nearly continuously exposed in two belts in the fault zone and each belt differs from the other in overall composition. In general, the Tertiary rocks become progressively finer grained up section and from east to west. Scattered outcrops of Tertiary volcanic rocks lie at the base of both Tertiary sedimentary sections.

The Quaternary rocks are mostly fan deposits, talus accumulations, and stream gravel derived from local hills in the fault zone and from the Avawatz Mountains. They have been subdivided into about 25 units based on sources of material in them, deformation, morphologic features, degree of pavement developed, and color (degree of desert varnish developed). By far, the bulk of the gravel clasts are dioritic in composition and can only have been derived from the Avawatz Mountains locally. Some fan deposits grade into less coarse material.

Faults. The oldest faults recognized so far trend approximately north and are moderately-steeply dipping. They probably extend southward into the Avawatz Mountains but have not been mapped to date. The faults along the northeast and north portion of the Avawatz Mountains are considered by most previous workers to be a continuation of the Death Valley and Garlock fault zones, which intersect near the northwest margin of the Avawatz Mountains (Fig. 1). The faults trend east to east-southeast and lie in a belt about two miles wide. The faults range in dip from 65° south to about 10° south. Movement along them appears to be reverse. The southernmost fault displaces Mesozoic diorite northward over Tertiary sediments and the northernmost fault displaces Quaternary gravel northward over Quaternary gravel. Faults between the northernmost and southernmost faults variously displace Tertiary, Mesozoic and Precambrian rocks. Rocks between faults tend to remain continuous laterally but portions of sedimentary sections may be cut out along the faults. For example, the Tertiary section near the diorite of the Avawatz Mountains may have the lower part of the section preserved at one locality and the upper part at another.

Deformation of the Precambrian and Tertiary sedimentary rocks ranges from steeply tilted to tightly folded. The greatest degree of folding is in gypsiferous siltstone, halite, and other fine grained strata. More competent rocks tend to be cut by abundant small faults rather than folded. The most common strike trend of sedimentary rocks is parallel to the main faults.

Conclusions based on progress to date.

1. The through-going faults along the north and northeast margin of the Avawatz Mountains are reverse faults. Movement characteristic of the Death Valley fault zone north (right lateral) and the Garlock fault farther west (left lateral) is not evident in the area mapped to date (Fig. 1).

2. The Tertiary sections exposed between branches of the fault zone contain clasts of diorite derived from the Avawatz Mountains and thus preclude any significant right or left lateral movement along the fault zone since late Tertiary time.

3. The Garlock fault either dies out in this region or branches farther north or south from a point west of the area mapped.

4. The structural complexity increases from east to west in the area mapped as the intersection area of the known branches of the Death Valley and Garlock fault zones is approached.

5. The similarity of diagnostic Precambrian sedimentary rocks in the Avawatz Mountains, Silurian Hills, southern Salt Spring Hills, and in the fault zones are probable evidence that there has been no significant lateral offset since Late Precambrian time.

6. The height of the Avawatz Mountains is probably about equal to the amount of reverse movement on the south dipping faults that lie along the north margin of the Avawatz Mountains.

Part B: Death Valley fault zone, south-central Death Valley.

Summary of progress to date.

General. The objectives of this work are to collect samples of a volcanic cone at the north end of the southern Death Valley fault zone and obtain K-Ar dates; make field investigations of wind-blown ash that was expelled from the cone and seek material suitable for age determination; determine the age of the time interval between fans that underlie and overlie the volcanic ash; collect samples for K-Ar dates of Tertiary volcanic clasts in Tertiary conglomerate offset by normal faults associated with movement along the Death Valley fault zone; and determine rate of movement along the normal faults since the volcanic clasts were deposited.

Discussion and Conclusion. Three samples were collected from the cinder cone for whole rock K-Ar determination but the results were negative. All known outcrops of ash were searched for buried plant remains but none were found. Trace fossils that appear to be cemented worm borings were found at several ash deposits and samples were collected for examination by an expert. It might be possible to obtain secreted organic material in the walls of the burrow traces suitable for C^{14} determination.

The principal discovery was that the ash was deposited on irregular terrain and preserved mainly on the walls of a few stream channels. The ash is also preserved beneath shoreline gravel formed when Lake Manly occupied Death Valley. It seems likely that the ash was deposited when Lake Manly existed.

Samples of volcanic clasts in the Tertiary sedimentary rocks were collected for comparison with local potential bedrock sources and were determined to be similar enough to collect samples next winter for K-Ar age determinations.

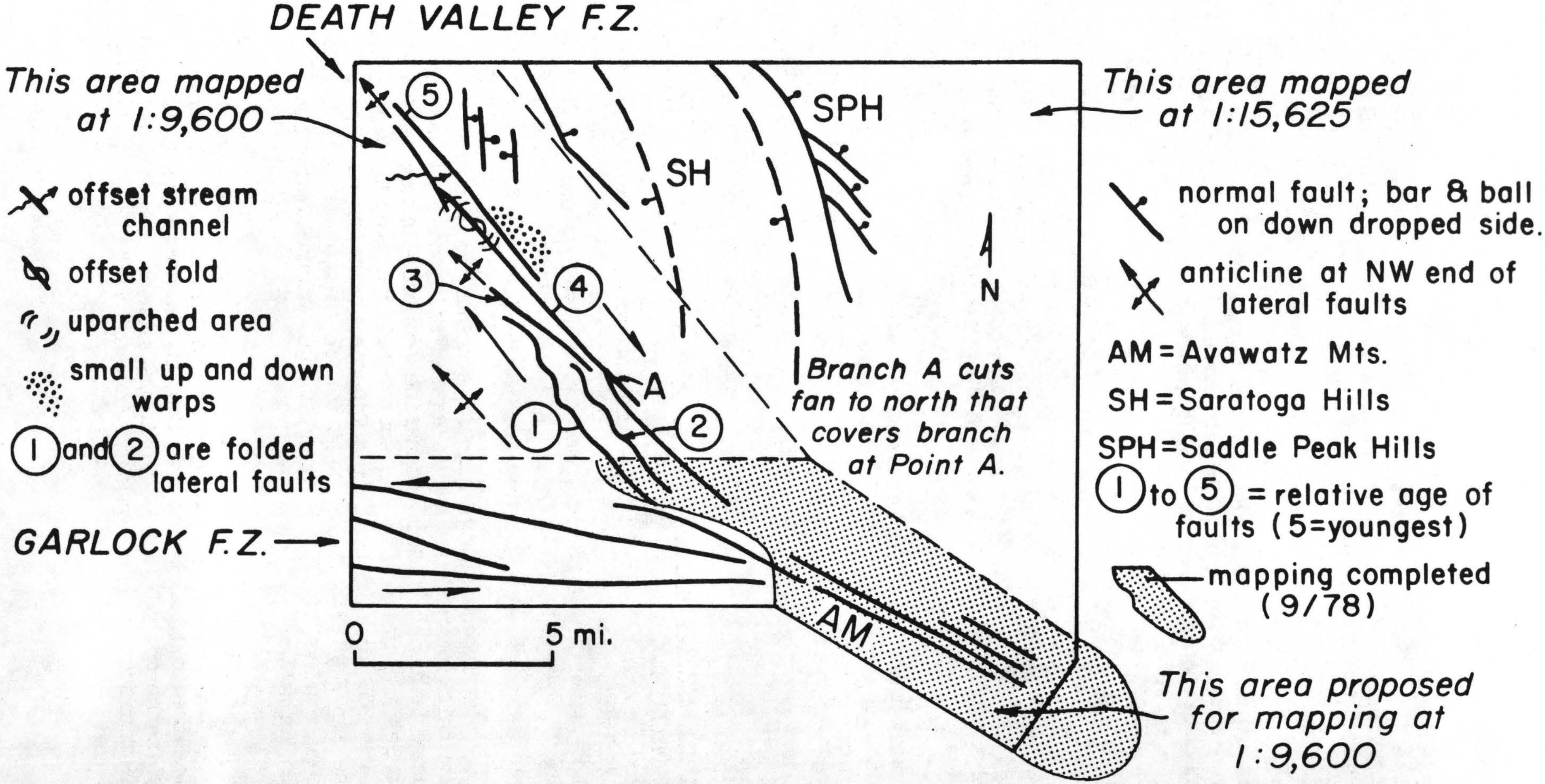

Figure 1. Sketch map of southeastern part of Death Valley fault zone and eastern part of Garlock fault zone, southern Death Valley, California (modified from Trona Sheet, Geologic Map of California)

Subsurface Geology of the San Gabriel, Holser, and Simi-Santa Rosa Faults, Transverse Ranges, California

USGS Contract No. 14-08-0001-16747

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SEMI-ANNUAL TECHNICAL REPORT SUMMARY

We have completed two subsurface structural projects on the San Gabriel fault (SGF), a study of the Honor Rancho oil field area by Jill Schlaefer and a study of the Newhall area by Fred Nelligan. During the summer, a study of the SGF from Honor Rancho north to Palomas Canyon was begun by Leonard Stitt, and a study of the western half of the Simi-Santa Rosa fault was begun by Mary Clare Jakes.

The Newhall area contains a Paleogene sequence that may intersect the SGF near its junction with the Whitney Canyon fault. Basement, found in the subsurface only south of the SGF, includes highly sheared diorite gneiss and granodiorite with subordinate amounts of limestone and alumina-excess schist which are probably part of the Paleozoic Placerita Formation. These rocks are a western extension of similar rocks exposed in the westernmost San Gabriel Mountains east of the Whitney Canyon fault. In the Continental-Phillips 1 well, the basement is in fault contact with a Paleogene sequence at least 1790m thick which includes, in ascending order, (1) unfossiliferous conglomerate; (2) dark gray to steel-gray siltstone associated with sandstone and conglomerate, age-equivalent to the Santa Susana Formation (Paleocene-Eocene), and (3) siltstone, sandstone, and conglomerate age-equivalent to the Llajas Formation (Eocene). The Eocene strata crop out in Elsmere Canyon and are found in many other wells in the Newhall area. The Eocene is overlain by a nonmarine sequence possibly up to 2000m thick consisting of variegated siltstone, sandstone, conglomerate, and rare bentonite. This nonmarine sequence is not easily correlated with the Sespe Formation to the southwest, the Mint Canyon Formation north of the SGF, or the nonmarine Topanga Formation of the Pacoima Hills in the San Fernando Valley. It is not in contact with marine Topanga in the Pico anticline, and it is overlain unconformably by the upper Miocene Modelo Formation.

The sliver of marine Paleocene rocks in Pacoima Canyon between the De Mille fault and the SGF may be an offset continuation of the Paleogene sequence at Newhall; the fossils in Pacoima Canyon, however, are older than any identified in the Newhall area. Juxtaposition of the two sequences of Paleocene rocks would suggest a minimum of 22 km of right slip along the SGF.

A subsurface ridge of basement rocks is found close to and southwest of the SGF in both the Newhall and Honor Rancho areas, possible a continuation of the narrow ridge of basement rocks found at Palomas Canyon, north of Castaic. At Newhall, the basement ridge appears to be in fault contact with Eocene rocks to the south; the fault is overlain unconformably by Modelo Formation. The basement was faulted against the Eocene along the Whitney Canyon normal fault prior to Towsley (Pliocene) deposition; later, the Whitney Canyon fault underwent reverse displacement after deposition of the Saugus Formation.

Both the Holser fault and SGF show evidence of late Quaternary movement near the junction of the two faults, Both faults have reverse separation, but the Holser dips southwest and the SGF dips northeast. The SGF changes strike at the junction such that the Holser fault, not the western segment of the SGF, is on trend with the eastern segment of the SGF.

The Pico anticline and Oat Mountain syncline appear to be geometrically related to the Santa Susana fault and thus probably formed in the last million years. From its surface outcrop northward to the axis of the Oat Mountain syncline, the Santa Susana fault is nearly parallel to bedding in the Topanga Formation of the hanging-wall block, and it dips north at a moderate angle. North of the Oat Mountain syncline, the Santa Susana probably steepens in dip beneath the Pico anticline and cuts across Topanga bedding. East of Aliso Canyon oil field, the Santa Susana fault bends sharply northeast and steepens in dip. The Oat Mountain syncline and Pico anticline bend northward and die out eastward, but are apparently replaced by reverse faults which increase in separation eastward. These reverse faults, all with the northeast side down, are the Weldon, Beacon, and Legion faults. If they are related to the Santa Susana Fault, they, too, must have formed in the last million years, and thus they should be examined for evidence of late Quaternary surface displacement.

Reports

Nelligan, Fred M., 1978, Geology of the Newhall area of the eastern Ventura and western Soledad basin, California: Semi-annual Technical Report, USGS Contract No. 14-08-0001-16747, and Ohio University M.S. thesis, Athens, Ohio.

Schlaefer, Jill T., 1978, The subsurface geology of the Honor Rancho area of the east Ventura and western Soledad basins, California: Semi-annual Technical Report, USGS Contract No. 14-08-0001-16747, and Ohio University M.S. thesis, Athens, Ohio, 86 p.

Yeats, Robert S., 1978, Neogene acceleration of subsidence rates in southern California: Geology, v.6, p. 456-460.

CALIFORNIA DIVISION OF MINES AND GEOLOGY

GEOLOGIC AND GEOMORPHIC INVESTIGATION OF THE SAN GABRIEL FAULT ZONE, LOS ANGELES AND VENTURA COUNTIES, CALIFORNIA

by F. Harold Weber, Jr.

U S G S CONTRACT NO. 14-08-0001-16600

SUMMARY REPORT COVERING PERIOD OCTOBER 1, 1976 TO SEPTEMBER 30, 1978

A two-year geologic mapping study of the fault zone between its apparent northwesterly terminus southeast of Frazier Mountain and Angeles Crest Highway, a distance of 90 km, has yielded abundant evidence that the zone has been active during late Quaternary time. Mapping this past year has shown, for example, that older alluvium of late Quaternary age is offset vertically as much as 10 m along faults of the zone in parts of the northeast Little Tujunga Canyon and Big Tujunga Canyon drainages.

Overall preliminary results of the study suggest that accumulated apparent right lateral offset along the segment of the fault zone in the Castaic-Newhall area may be only 5-10 km, in contrast to the generally accepted figure of at least 50 km. My estimate is primarily based (1) on comparison of exposures of igneous-metamorphic terranes along both sides of the fault and projection of pertinent concealed contacts of these rocks; and (2) on comparison of clasts within oldest Violin Breccia of late Miocene age on the northeast side of the fault in lower Violin Canyon to igneous-metamorphic rocks exposed nearby to northwest along southwest side of the fault. Apparent right lateral offset of Pleistocene beds of the Hungry Valley Formation just south of the northwest terminus of the fault is about 1 km; whereas the maximum apparent right lateral offset of Pleistocene beds of the Saugus Formation in the Honor Rancho area is less than 1 km.

Thus, the preliminary conclusions of the study are (1) that the San Gabriel fault has had an average rate of right lateral movement since the beginning of late Miocene time of roughly 0.5-1 km each 1,000,000 years; (2) that right lateral offset continued into middle and late Quaternary time; (3) that latest Quaternary movements appear to be small and perhaps mostly vertical; and (4) that the zone is now geologically active and that movements along it possibly could yield earthquakes in the range of M 6-7, based on geologic and geomorphic evidence.

Earthquake Hazards Studies, Ventura basin and adjacent areas, southern California

8-9540-01615

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Investigations

1. With C. G. Bufe and R. P. Maley, mapped, evaluated, and reported on the surface effects, damage, seismicity, and geologic-tectonic setting of the May-July 1978 earthquake sequence near Thessaloniki, Greece.

2. With H. W. K. Lee, mapped, analyzed, and reported on the Santa Barbara earthquake of August 13, 1978 and its aftershocks.

3a. Continued detailed mapping of relations between three dated, uplifted marine terraces, equivalent fluvial deposits, and several faults along the Point Conception-Ventura coast. Continued collecting and dating mollusks from marine terrace deposits and ashes from late Tertiary-Quaternary sequence. Work done in cooperation with OEG project 9540-01947 (Sarna-Wojcicki), OES project 9940-01623 (La Joie), and OES grant 14-08-0001-G247 (Wehmiller).

3b. Late Quaternary fault displacements in the Pitas Point-Punta Gorda area were measured and rates of displacement calculated from offsets of uplifted marine terrace platforms previously dated by radiocarbon and amino-acid racemization techniques.

3c. Vertical tectonic uplift rates were calculated from uplifted, dated marine terrace platforms in the Pitas Point-Punta Gorda area. Vertical component of tectonic uplift was also estimated from geometric reconstruction of the Ventura River.

4. A preliminary surficial deposits map of the Oxnard-Ventura area at a scale of 1:125,000 was compiled from existing soil-series and geologic maps.

5. Two reports on the 1970-1975 seismicity and late Quaternary deformation of the western Transverse Ranges (CA), previously prepared as chapters in a projected Professional Paper report on the entire province (see Summaries of Technical Reports, vol. VI, June 1978, p. 38-40), were revised for earlier publication as an MF map and Circular (see under Reports).

Results

1. The June 20, 1978 mainshock (M 6.5) occurred 25-30 km east of Thessaloniki, Greece, in an agricultural area between Lakes Langadha and Volvi, an

area of recurrent moderate-large earthquakes. A 10 km zone of right-steeping, en echelon surface ruptures trends northwest between the lakes and through the villages of Skolari and Stivos. A second 5 km zone of normal-fault ruptures follows an east-trending fault-line scarp along the south margin of the valley between the lakes, through three villages, and merges with the Skolari-Stivos rupture zone at its southeast end. The Skolari-Stivos zone lies along the faulted boundary between the pre-Mesozoic, crystalline-schist Rhodope massif on the northeast and the intensely deformed Vardar root zone of Mesozoic metasedimentary and ophiolitic rocks on the southwest.

The one operating accelerograph in Thessaloniki on June 20 recorded a maximum acceleration of 0.13 g; duration of shaking at 0.1 g or greater was about 1¼ sec. The accelerogram suggests that the June 20 event was a complex rupture consisting of two events, M 6¼ and M 6½, within a few seconds. Fault-plane solutions for 4 of the larger (M5-6½) events are consistent with left-reverse-oblique slip on the Skolari-Stivos fault. Inferred principle stress orientations are near-horizontal, east-west compression and north-south tension, a pattern that characterizes the north Aegean Sea region north of lat. 39° N and east of long. 22° E. This region is bounded on the south and southeast by an inferred northward-dipping accretionary Benioff zone postulated by Papazachos (1976) on the basis of bathymetry and distribution of earthquake hypocenters. The map extremities of the Benioff zone trend generally toward the northwest-trending Vardar root zone on the west and the North Anatolian fault on the east. The left slip on the east boundary of the Vardar zone (site of the 1978 faulting) and the right slip along the North Anatolian fault may thus relieve the east-west compressive stresses of the region.

2. The M 5.1 Santa Barbara earthquake of August 13, 1978, occurred at lat. 34° 22.2' N., long. 119° 43.0' W., 4 km south of Santa Barbara, at a depth of about 12.5 km in the northeast Santa Barbara Channel, part of the western Transverse Ranges structural province. This part of the province is characterized by seismically-active, east-trending reverse faults and unusually large rates of coastal uplift, averaging about 10m/1000 years over the last 45,000 years.

No surface rupture was detected onshore. Subsurface rupture offshore propagated 11 km northwest from the mainshock hypocenter to the shoreline at Goleta, 15 km west of Santa Barbara. At Goleta a maximum ground-level acceleration of 0.44 g was measured and extensive minor damage occurred; only minor injuries were reported. A fairly well-constrained fault-plane solution of the main shock and distribution of the aftershocks show that left-reverse-oblique slip occurred on a west-northwest-trending, north-dipping reverse fault; inadequate dip control precludes good correlation with any of several mapped faults. The fault-plane solution and aftershock pattern closely fit the model of regional deformation previously reported (Summaries of Technical Reports, vol. VI, p. 38-40) and the solution closely resembles those of 5 previously-mapped events located within 15 km.

3. Offset rates of onshore faults along the western west-plunging part of the Ventura Avenue anticline range from 0.5 to 1.6 mm/year over periods of 2500 and 45,000 years BP. Offset rates for the Javon Canyon fault, which

offsets both the 2,500- and 45,000-year marine terrace platforms, are about the same (1.5 and 1.1 mm/year; Table 1). In comparison, previously-reported maximum vertical separation rates on the Red Mt. fault calculated from subsurface data are as high as 13 mm/year over approximately the last 0.5 million years, immediately north of the structural high of the Ventura Avenue anticline.

Vertical tectonic uplift rates of 2.2 to 9.3 mm/year were calculated from uplifted, dated marine terrace platforms onshore in the Pitas Point-Punta Gorda areas. Along the coast, the uplift rates increase systematically from near Punta Gorda on the northwest, plunging limb of the Ventura Avenue anticline to the southeast (Table 1). Highest uplift rates (9.3 mm/year) coincide with the structural high of the Ventura Avenue anticline north of Pitas Point, decreasing again towards the southeast near Ventura, on the south limb of the anticline. Uplift rates calculated from geometric reconstruction of the Ventura Avenue anticline are highest along the highest structural part of the anticline east of the Ventura River (13.6 mm/year), and somewhat lower to the west, east of Pitas Point, along the west-plunging part of the anticline (11.7 mm/year), using an amino-acid age of 200,000 years BP for the youngest deposits involved in the folding.

Considering the above evidence, maximum deformation as expressed by both rates of faulting and rates of vertical uplift coincide with the structural high of the Ventura Avenue anticline. Folding and faulting have continued at about the same rates over the last 0.2-0.5 million years. Maximum historical uplift rates of about 10 mm/year derived from geodetic data compare closely with rates obtained from long-term geologic uplift rates.

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Table 1. Comparison of fault displacement and regional tectonic uplift rates along the Ventura Avenue Anticline

Fault Displacement Rates

Area	Fault	Age of offset horizon (yr b.p.)	Sense of displacement	Amount of displacement(m)	Rate of displacement(mm/yr)
east	Red Mountain, main branch	0.5-1.0 m.y.(?)	north up	6,500	6.5-13.00
	Javon Canyon Fault	45,000 yrs.	south up	48.8	1.1
	Padre Juan Fault, east end	do	north up	67.1(min.)	1.5 (min.)
	Javon Canyon Fault	2,500[1] yrs.	south up	4.0	1.6
	Padre Juan Fault, central part	45,000 yrs.	do	30.5	0.7
	Red Mountain Fault, SW branch	do	north up	24.4(min.)	0.5 (min.)
	Red Mountain Fault, SW branch	do	do	21.3	0.5
	Red Mountain Fault, SW branch	45,000 yrs.	do	73.2(max.)	1.6 (max.)
west	Red Mountain Fault, central(?) br.	do	do	67.1	1.5

Regional Tectonic Uplift Rates from Geometric Reconstruction of Anticline

Area	Location	Age of youngest folded sediments	Amount of uplift above sea level(m)[2]	Rate uplift (mm/yr.)
east	Structural high east of Ventura R.	0.2 m.y.	2720	13.6
	Structural high east of Pitas Point	0.2 m.y.	2340	11.7

Regional Tectonic Uplift Rates from Uplifted Marine Terraces

Area	Location	Age of Uplifted marine terrace (yrs. b.p.)	Amount of uplift above sea level(m)[2]	Rate uplift (mm/yr.)
	Ridge east of Padre Juan Canyon	45,000(?) yrs.	418.3	9.3
	Ridge west of Padre Juan Canyon	do	368.9	8.2
	Coast between Pitas Point and Javon Canyon	2,500 yrs.	15.2	6.1
west	Punta Gorda	45,000 yrs.	97.4	2.2

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[1]Offset feature is Holocene stream terrace graded to uplifted marine platform radiocarbon dated at 2,500 yrs. b.p.

[2]Sea level at 2,500 yrs. b.p. is considered equivalent to present sea level. Sea level at 45,000 yrs. b.p. is considered to have been 55m below present sea level.

Southwestern Utah Seismotectonic Studies

8-9950-01738

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Investigations

1. Field studies of late Quaternary geology and morphology of fault scarps in the Beaver Valley area, Beaver County, Utah.

2. Field studies of the Hurricane fault near Cedar City, Utah.

3. Field studies of Neogene structures in the Drum Mountains, Confusion Range, northern and southern House Range, Conger Range, Burbank Hills, and Tunnel Spring Mountains, western Millard and Juab Counties, Utah.

Results

1. Preliminary study of calcic soils in Beaver Valley has shown that pedogenic carbonate of contrasting stages of development has formed on terrace and pediment surfaces of contrasting age. At least five surfaces of contrasting age are recognized. The oldest has a mature calcrete formed on it and is offset by at least 50 northerly trending faults with indicated normal surface displacements of as much as 25 m. Progressively younger surfaces are offset by fewer faults with lesser indicated displacements, and the youngest surfaces are not faulted and have no apparent calcic soil developed on them. Faulted surfaces are back-tilted toward the faults in such a way that there is little or no net offset across a series of parallel faults of similar displacement direction. The faulted and tilted surfaces can be divided into an eastern set with westerly displacements and easterly rotations and a western set with easterly displacements and westerly rotations. Quaternary deposits that predate the oldest surface were faulted and tilted in the same manner on the same structures prior to formation of the oldest surface by erosional planation. On the basis of K-Ar and fission track age determinations and tephra typing, supplied by Harald Mehnert, Charles Naeser, and Glenn Izett, respectively, the oldest surface is probably younger than about 0.6 m.y. The young unfaulted surfaces are Holocene.

The area offers a potential for estimating ages of late Quaternary fault events by multifaceted techniques that include K-Ar and fission track dating, tephra typing, rate of soil carbonate accumulation, U-series dating, and obsidian hydration dating; all studies of which are underway by USGS personnel and others. The results should provide a much-needed basis for assigning ages to reference relationships between scarp height and scarp slope angle formulated from morphometric studies of fault scarps in the Beaver Valley area.

2. Geologic and geomorphic relationships cited by previous investigators as evidence for pre-Quaternary displacement on the northern part of the Hurricane fault have been thoroughly evaluated and, for the most part, are found to be inaccurate or inadequate. The structural foundering of the St. George basin relative to the adjacent Colorado Plateaus province on structures such as the Hurricane fault was largely a Quaternary event. If the Hurricane fault in the Cedar City area is to be regarded as the boundary between the Colorado Plateaus and Basin and Range provinces, it assumed that role late in the Cenozoic tectonic history of the region. A detailed report of these findings is 90 percent complete.

3. Mapping of bedrock in selected areas of western Millard and Juab Counties has provided a large block of geologic data indicating episodes of major Neogene tectonism there. The data indicate mountain-building events (probably mostly by block faulting and thin-skinned extensional tectonics) at sites largely unrelated geographically or structurally to the existing mountain ranges. This picture of Neogene tectonism is greatly different from published accounts which depict the area as having undergone extensive normal faulting prior to Neogene time and as having been relatively quiescent structurally since then. The area is uncommonly aseismic and lacks evidence of late Quaternary faulting, but, based on the new findings, these features can not be related to structural inactivity during the late Tertiary.

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Seismotectonic Analysis
Rio Grande Rift, New Mexico

8-9530-01556

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Investigations

1. Continued synthesis and analysis of regional data on Precambrian through Quaternary rocks from published sources, reconnaissance examinations, and original fieldwork.

2. Began compiling regional structural cross sections from Colorado Plateau across rift to Great Plains.

3. Participated in International Symposium on Tectonics and Magmatism of Rio Grande Rift as field trip leaders, keynote speaker in session on Age, Extent, and Structural Style, and author of invited paper in Guidebook to Rio Grande rift.

4. Completed synthesis of existing geologic mapping for Albuquerque-Socorro region which is the most seismic part of the rift. The map of the Socorro 1° x 2° quadrangle provides new stratigraphic classifications needed to interpret ages and styles of deformation.

5. Began trenching along young Water Canyon Fault Zone, west side of La Jencia Basin near Socorro. This lengthy fault zone in the region of highest seismicity has slightly dissected scarps and closed depressions on the downthrown side. Soil and geomorphic data are being analyzed to determine ages and history.

Results

Synthesis of paleostratigraphy and paleotectonics provides a state-of-the-art assessment of the regional tectonic history of the region of the rift in north-central New Mexico--an area of about 53,000 km^2. Partial results of the synthesis are shown on figure 1. A conclusion supported by work to date is that the rift structures in north-central New Mexico are geologically new. Undoubtedly, parts of some structural elements are controlled locally by renewed action of Precambrian and younger structural features; however, late Miocene through early Pleistocene faulting and tilting of very large blocks disrupted major Precambrian fold systems, and disrupted an ancient and long-lived system of north-northwest trending uplifts and basins that was established in Pennsylvanian time and that maintained its general trends and identities through the Mesozoic era and into early and, perhaps, middle Tertiary times. For example, the region of the Neogene San Luis Basin, from about Taos, New

Mexico, northward into Colorado, previously stood as the sediment-shedding Uncompahgre uplift in late Paleozoic and parts of Mesozoic time, and was part of an uplifted "backbone" of the Laramide Sangre de Cristo-Brazos geanticline. Yet, this former positive area foundered and became a basin in Neogene time.

A concept of east-west regional extension and mantle upwelling has been favored by some writers for the Neogene origin of the rift. However, current structural and stratigraphic data do not seem to indicate much extension in north-central New Mexico. As shown in figure 2, the Neogene normal faults in the Espanola Basin only slightly modify the synclinal shape of the basin. Stratigraphic data indicate that the bounding Nacimiento and Sangre de Cristo uplifts rose concurrently with the downwarping of the basin. Prior to 7 or 8 million years ago the deformation may have been mainly compressive, as was the preceding Laramide deformation. This segment might exhibit a "locked," relict condition; its structural style and history are considerably different from other parts of the rift, particularly the Albuquerque-Socorro region. If this analysis is correct, it may partly explain the very low seismicity of the Espanola Basin as contrasted to the higher seismicity and numerous young faults of the Albuquerque-Socorro basins. However, the rifting process may be operating currently in the Espanola Basin; Reilinger, Brown, and Oliver report that leveling data show 4.9 cm subsidence in the deep part of the basin between September 1934 and March 1939.

Continuing analysis of physiographic and volcanic features in the western Great Plains in north-central New Mexico indicate Neogene erosion and volcanic activity concurrent with regional uplift. Therefore, the Rio Grande rift is within and near the eastern margin of a very large region of epeirogenic uplift. This region includes the western margin of the Great Plains, the southern Rocky Mountains (and rift), and the Colorado Plateau. If the rift is viewed as a broad and pervasive "system" of Neogene faults, it might be interpreted as the eastern vagaries of slight intraplate shifting, and stretching and shattering of large areas during regionally varying amounts of this epeirogenic uplift.

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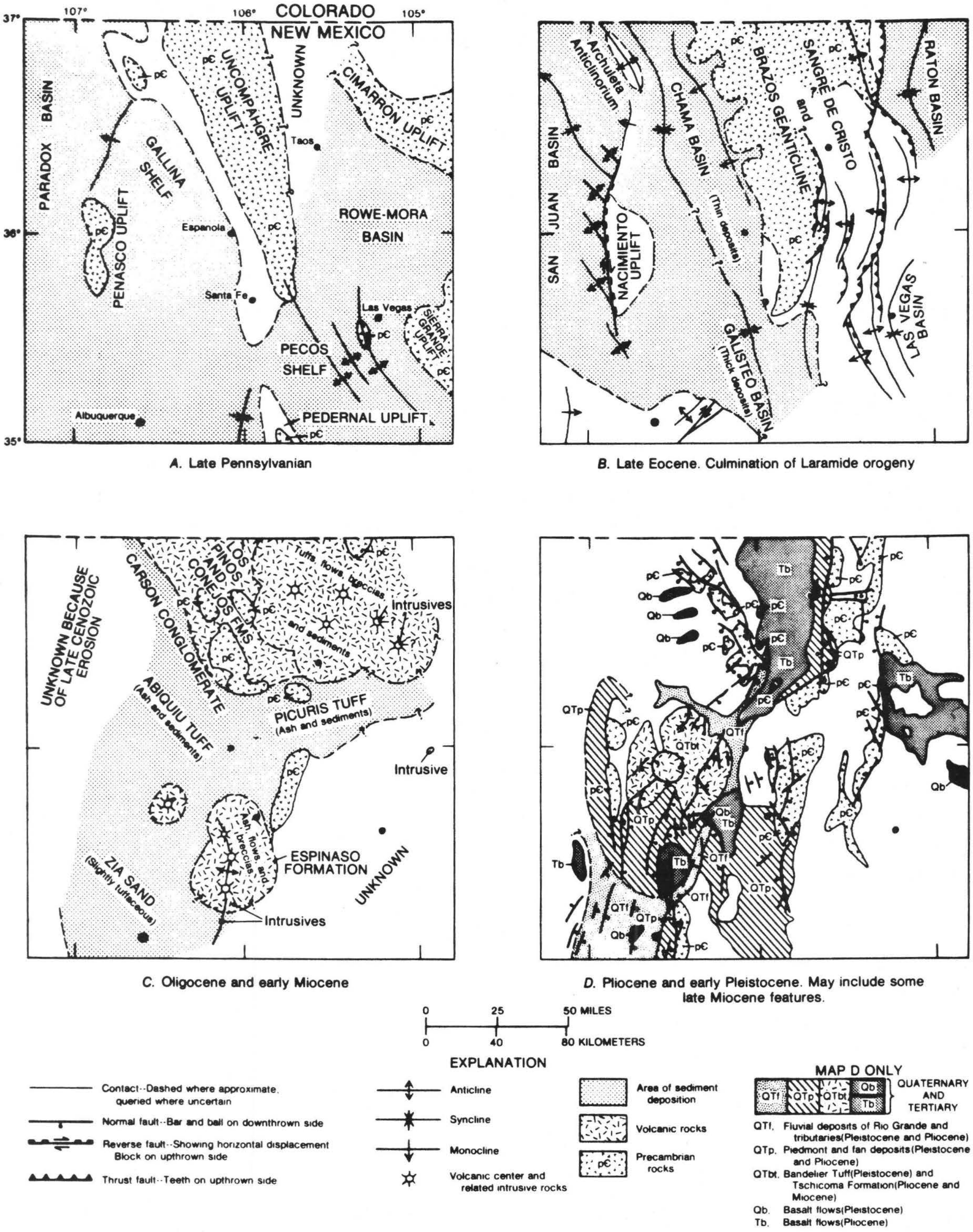

Fig. 1--Paleotectonic diagrams of north-central New Mexico showing (map D) principal Neogene faults of Rio Grande rift system (Baltz, 1978, p. 223)

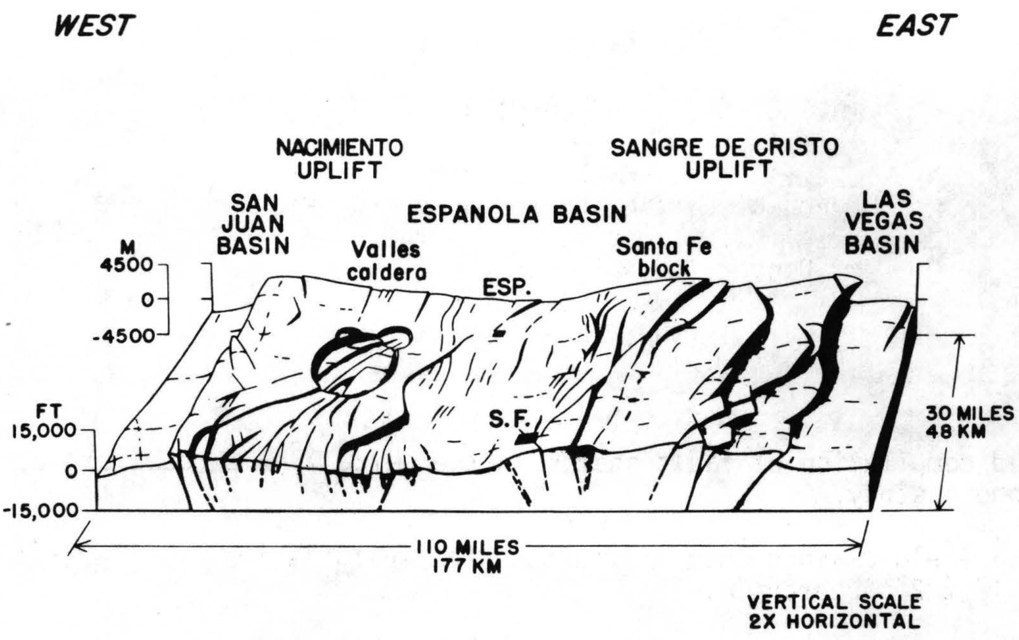

Fig. 2--Block diagram of Rio Grande rift and adjacent uplifts in latitudes of Santa Fe and Espanola, N. Mex.

Northwestern Utah Seismotectonic Studies

8-9950-01737

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Investigations

1. Completed compilation of fault scarps in the Delta 1° x 2° quadrangle, Utah, based on airphoto study.

2. Completed field measurements of fault scarps suitable for profile studies in the Delta 1° x 2° quadrangle.

Results

1. Studies of the morphology of fault scarps within a west-northwest-trending zone of late Quaternary faulting that extends across central western Utah from Nevada to the Wasatch Plateau show that the zone has been active in Holocene time. The scarp morphology studies indicate that scarps younger than the Lake Bonneville shoreline (between 12,000 and 15,000 years old) span the entire zone.

2. A radiocarbon date on a charcoal sample from a fault scarp in alluvium along the Wasatch fault near Mona, Utah, shows that the conspicuous faulting in that area occurred within the last 4,580 years (sample W-4057). The date is the first documentation of Holocene faulting on the Wasatch fault.

Reports

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SEISMOTECTONIC AND GEOMORPHIC EVOLUTION OF THE HOLOCENE BLACK ROCK FAULT, NORTHWESTERN NEVADA

Summary Report of the
First Nine Months of Work

U.S. Geological Survey Grant No. 14-08-0001-G-505
Period Jan. 15, 1978- Jan. 14, 1979
Principal Investigator: L.T. Grose

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Purpose

The purpose of the research is to investigate fault scarp degradation as related to age of faulting, control of material faulted on rates of degradation, and recurrence intervals of faulting associated with a typical dip-slip fault in the Basin and Range Province. The Black Rock Fault (BRF) in northwestern Nevada is the subject of our study.

Research Activities

1. Phototectonic mapping of the BRF zone was completed during March through May 15, 1978.
2. All sedimentary and bedrock units near the fault zone were mapped and differentiated as "faulted" or "nonfaulted."
3. All branches of the BRF zone, and all associated deformational features, were mapped and described.
4. Slope angles and heights of scarps associated with the BRF were recorded in the form of profiles perpendicular to the scarp.
5. Age-datable material was collected from several units that should provide ages of fault displacement.
6. Trenches were dug through the fault zone at six sites to facilitate study of age relationships, offsets, and repeated movements.

Results

1. Black and white low sun angle photographs (LSAP) at scale 1:24,000 were taken of the entire BRF zone. They are excellent photogeologic

mapping bases and, in conjunction with topographic maps at the same scale, served as excellent field map bases. Evidence of late Quaternary tectonic activity on the BRF as revealed on the LSAP includes: 1) fault scarps, 2) linear sand dunes, 3) vegetation linears, 4) ground water anomalies such as springs and local dense vegetation, and 5) abrubt linear contrasts in microgeomorphic forms, mainly drainage density.

2. Eight Quaternary sedimentary deposits and two Miocene bedrock units are offset by the BRF. The oldest unit offset is a Miocene basalt; this fault is not marked by a scarp. The second oldest unit offset is a sequence of Miocene ash falls, ash flows, and tuffaceous sediments. Late Pleistocene lake deposits and late Pleistocene and Holocene alluvial deposits are also offset. The only unit not offset by faulting consists of active and vegetation-stabilized sand dunes that are probably younger than 1000 years.

3. The BRF zone consists of 27 parallel and en echelon breaks ranging in length from less than one km to about 15 km. The most outstanding deformational features associated with the BRF are fault scarps; 26 of the 27 breaks are marked by scarps. The scarps range in height from tens of centimeters to over 9 meters, and are often remarkably sharp and well-preserved, especially where sustained in gravels. Profiling of the scarps and up and downthrown blocks of the faults revealed pervasive gentle eastward tilting of both blocks along the down-to-the-west BRF. Less pervasive but still common is the presence of narrow graben-like subsidence zones parallel to the fault on the downthrown side. Well-preserved and actively developing cracks or rifts, parallel to the fault zone at its southern end, were monitered throughout the field season (May 18- October 13). These cracks are strong evidence for modern tectonic tension in the area.

4. Profiles of fault scarps were measured at 103 localities along the 60-km length of the BRF zone. Measurements were made on well-preserved scarps, on scarps affected by wave action, on single scarps cutting several different materials, and on scarps showing marked changes in strike. Scarps are preserved along the BRF zone in course alluvial gravels, lake-deposited and reworked

gravels and sands, clay, and tuffaceous sedimentary rocks. Correlation and analysis of data is in a preliminary stage, but several observations are evident.

A. Profiles on several scarps show step-like configuration, suggestive of at least 2 periods of fault movement.

B. Based on comparison of slope angle and crest rounding, the fault scarps can be separated into two relative age groups.

C. Grain size of material faulted is an important control on rates of scarp degradation. Several individual breaks along the BRF zone cut more than one kind of material. Based on study of these individual fault breaks, there is a direct relationship between the grain size of unconsolidated materials cut by the fault and the rate of degradation of the fault scarp. Scarps sustained in gravels are the best preserved, with those in sand and clay being progressively more degraded, along a single break. This relationship appears to apply to all scarps in the same relative age group. The typical maximum slope angles in gravels are 34°, in sandy sediment about 30°, and in clay only about 22°.

5. Deposits associated with fluctuations of late Pleistocene and Holocene lakes in the Lahonton Basin provide the most important time markers for age-dating movements on the BRF. Age-datable material offset by faulting includes at least 3 ashes in Lake Lahonton sediments, tentatively identified as less than about 24,000 years old. Also, lithoid tufa and ostracods of late Pleistocene age are offset. In-situ pelecypod shells, tentatively related to a Holocene (less than 5,000 years old) high stand in the Black Rock Desert basin, are younger than one episode of faulting on the BRF, and older than another episode. Alluvial deposits offset by faulting were generally lacking in age-datable materials, but one sample of wood was collected from a channel deposit in the upthrown block of the fault. A fossil root zone, offset by faulting, was also sampled.

6. Six carefully selected sites along the fault were trenched and thoroughly described and sampled. These trenches yielded valuable information on the relationship of the fault plane to the surface scarp, and on the total amount of offset as related to modern scarp

height. The trenches were also important in exposing age-datable materials offset by faulting. Three trenches show strong evidence for two periods of faulting younger than about 24,000 years, and at one trench site evidence supports at least four and probably five fault movements younger than 24,000 years. Relative ages of three periods of fault activity can probably be defined from this trench alone, based on ash, ostracods, and a buried root zone.

Future Research Activities

1. Age dating of ash, tufa, wood, and shell materials.
2. Correlation of absolute ages of faulting with data on scarp morphology.
3. Definition of recurrence intervals of faulting, and possibly of relative magnitude of seismicity.

Anchorage-Susitna Lowlands Earthquake Hazards Mapping

8-9310-02078

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Investigations

1. Initiated field studies in the Beluga area, Anchorage Borough, and along the Anchorage to Fairbanks highway/railroad belt.

2. Established a computerized storage and retrieval system for existing subsurface engineering soils data obtained from private, state, and federal organizations.

3. Cooperated with Harold Olsen, Branch of Engineering Geology, U.S. Geological Survey, who is carrying out a drilling and sampling program of the Bootlegger Cove sediments in the Turnagain Heights area, Anchorage--site of the large earthquake-induced landslide which occurred in March, 1964.

Results

1. Completed surficial/engineering geologic mapping in the Beluga area, in the Anchorage Borough, and along the Anchorage to Fairbanks highway/railroad belt.

2. Had coordination meetings with various members of the Branch of Engineering Geology and of the Water Resources Division who are, or are planning to work in the Anchorage-Susitna Lowlands region.

3. Had meeting with the Municipal Geotechnical Advisory Commission, Anchorage in order to discuss the scope and objectives of the Anchorage-Susitna Lowlands Earthquake Hazards Mapping project.

Seismo-Tectonic Analysis of Puget Sound Province

8-9540-02197

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Investigations

1. The large Seattle-Bremerton gravity anomaly is being studied by an analysis of bedrock and surficial geology, marine seismic profiles, seismicity, aeromagnetics, and regional gravity. A refraction seismic line is planned across the western end of this feature northwest of Bremerton. The principal product of this study will be a seismo-tectonic map of the 1:100,000-scale Seattle sheet.

2. A 1:100,000-scale bedrock geologic map of the Port Townsend sheet is underway.

3. A tectonic map is being made of the eastern strait of Juan De Fuca area from a detailed study of marine seismic profiles, aeromagnetics, gravity and regional geology.

4. A seismic response map is being made of a portion of the southern Seattle urban area (Seattle South and parts of the adjoining Duwamish 7-1/2' quadrangles). Surface and subsurface lithologic and physical property data are being used to group geologic units into units with similar response to seismic shaking. Use of the relationship between seismic wave velocity and shaking intensity, as observed in the San Francisco Bay area, will be used in conjunction with consideration of thickness variations of the defined units.

Results

Geologic mapping in the Seattle area has resulted in the identification of previously unrecognized bedrock structures. Overturned Oligocene strata north of Issaquah and steeply dipping Oligocene and Quaternary(?) strata in Eastgate have refined the location of the Seattle-Bremerton structure east of Seattle.

Eighteen one-second sweep acoustic-reflection profiles for the Parizeau cruise (in the eastern Strait of Juan De Fuca) have been interpreted and the results are being plotted on maps. In addition, about 80 percent of the 1/4-second sweep (high resolution profiles) from the same cruise have been interpreted.

Geologic field investigations along the prominent arcuate topographic feature in the western Cascade Range east of Seattle failed to show any faulting in the bedrock or surficial deposits.

A seismo-tectonic model has been devised for the Puget Sound Region. Earthquake hypocenters suggest an arcuate east-dipping surface about 50 to 70 kilometers beneath the Puget Sound Lowland. This arcuate pattern parallels the eastern margin of the horseshoe-shaped outcrop of the Early Eocene Crescent Formation on the Olympic Peninsula and the arcuate thrust faults in the core of the Olympic Mountains. Similarly, to the east, the Quaternary volcanos in the northern Cascades define an arcuate pattern paralleling the seismic surface beneath Puget Sound. Depths to the magma source beneath the Quaternary volcanos, inferred from their geochemistry, are compatible with an eastern extrapolation of the arcuate seismic surface, suggesting that the seismic surface may define the upper surface of a subducted oceanic slab. The maximum occurrence of seismicity is localized in the inferred overlying continental plate at the apex of the arcuate east-dipping seismic zone.

Wasatch Front Surficial Geology

8-9550-01622

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Investigations

1. Completed the compilation of the distribution of surficial materials bounding the Wasatch Front in the Great Salt Lake Valley on a 1:125,000 scale topographic base, and completed 50 percent of the compilation in Utah Valley to the south, with the ultimate use of these compilations being their application to development of a physical property map from which data can be utilized in the interpretation of ground-motion response to earthquakes and applied to microzonation maps for this urban corridor. Completion of the compilation of the Utah Valley area is awaiting the availability of the new Provo Special 1:100,000 scale base being prepared by the U.S. Geological Survey's Topographic Division.

2. The surficial materials compilation utilized the Kern PG-2 plotter on which high-altitude aerial photographs were interpreted, coupled with use of published geologic maps and articles, and the Department of Agriculture Soil Conservation Service county soils maps and reports. The plotter permitted accurate placement of map unit boundaries of materials selected on the basis of their genetic and textural properties. Origins of previously unmapped deposits were determined by standard interpretive techniques with emphasis on geographic and geomorphic distributions, attributes that are prominant in optical stereo-device-controlled compilations.

3. Physical properties of the unmapped materials were interpreted from Soil Conservation Service parent soil materials descriptions; these in turn were coded into the compilation according to texture and other physical characteristics. Such pertinent data would be available as criteria suitable for preparation of two maps: a surficial geologic map and a map of the physical properties of the unconsolidated materials along the Wasatch Front.

4. Surficial map units were evaluated by reconnaissance field investigations to confirm physical property and geologic interpretations. Selected localities were sampled for additional physical property data to be determined in the Engineering Geology Branch laboratory.

Results

1. Completed laboratory testing of undisturbed samples obtained from the 5-hole drilling program instigated earlier, and from the surface outcrops.

2. Calculations and interpretations of surface and in-hole geophysical data completed by C. H. Miller, Engineering Geology Branch.

3. Completed and field checked a surficial geologic map for the Salt Lake Valley area as compiled from the coded materials map.

4. Selected geologically controlled localities for seismograph installation in the Salt Lake City, Provo, and Ogden areas in order to monitor nuclear events and quarry blasts in support of the Ground Response, Salt Lake City Region, project, W. W. Hays, Project Chief.

5. Collected samples suitable for radiocarbon determinations from localities believed to be applicable to establishing ages of surfaces related to the lowering of Lake Bonneville during the last 15,000 years. Such dates would be helpful in (a) establishing definitive stratigraphic sequences within that time span, and (b) establishing limits that could be applied to surfaces disrupted by faulting.

6. Determined an area of about 13 square kilometers between Ogden and North Ogden to be a previously unrecognized liquefaction slide similar to the Farmington slide north of Salt Lake City, as described by R. Van Horn, Engineering Geology Branch. The distribution of such large liquefaction slides strongly suggests that the entire East Shore of the Great Salt Lake may be susceptible to liquefaction from earthquakes.

Reports

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Alaska Geologic Earthquake Hazards

9-9310-01026

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Investigations

1. Using R/V Sea Sounder high solution reflection seismic data were obtained along the offshore projection of the Fairweather fault to locate the fault trace and to determine the late Cenozoic displacement history.

2. Helicopter-supported field studies were made along the Denali fault trace from the Haines area to the Canadian border, and high resolution seismic reflection surveys were conducted with the R/V Sea Sounder along the extension of the fault system beneath Chatham Strait and Lynn Canal.

3. Helicopter-supported field studies were made of marine terrace sequences in the Lituya Bay area to determine the style and history of terrace uplifts and their implications for earthquake recurrence.

Results

1. A probable extension of the Fairweather fault was traced for over 72 km on the continental shelf off Chichagof and Baranof Islands, but a gap of 50 km exists where the fault could not be detected from the point where it runs offshore at Palma Bay southeastward across Cross Sound. The mapped segment is marked by surficial scarps with up to 10 m relief and is closely alined along the focal region of the 1968 Sitka earthquake.

2. No evidence was found either onshore or offshore for Quaternary displacement along the southeastern end of the Denali fault system. Early Tertiary leaf-bearing sedimentary rocks along the fault near the border with Canada have been deformed by dextral shear. The data suggest that the most recent displacement of the fault is Neogene or pre-Quaternary.

3. Interpretation of the Lituya terrace sequences suggest that they formed by a combination of regional and local tectonism. Five wave-cut surfaces were probably uplifted during major tectonic earthquakes and average uplift rates are 1 cm/yr or more. Pronounced warping of the terraces is interpreted as related to growth of a relatively local anticlinal structure along the coastal belt. Because terrace sequences in the eastern Gulf of Alaska appear to be related to local anticlines, there is no lateral continuity or height correlation between terrace sequences.

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Quaternary Geology of the Wasatch Front

8-9530-02174

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Investigations

1. Studies of Quaternary stratigraphic sections and landforms along the Wasatch Front in Salt Lake and Utah Valleys and near Ogden.

2. Excavations in the large gravel pits at Little Valley, near Promontory Point, to expose (and to reexpose) key stratigraphic units and relationships and to obtain materials for dating.

3. About 100 profiles of fault scarps at selected locations along the Wasatch Front have been measured by James Petersen (University of Utah). The purpose of the work is to collect data on amount of offset of surfaces of different ages, to use morphology of scarps to estimate age of faulting, and to study the processes and rates of fault-scarp modification.

4. Field consultation with scientists from Woodward-Clyde on the stratigraphic interpretation of Lake Bonneville deposits exposed in and near their trenches across fault scarps near Kaysville and Springville.

Results

1. The history of the decline of Lake Bonneville from its last high stand is of importance to tectonic studies as the event may define a maximum age for fault scarps lying below the various shorelines in the Bonneville basin. Reexamination of key exposures in the Cottonwood delta area, particularly along Dry Creek, and on the north side of the Weber River trench near Ogden has provided information for a possible solution to a long-standing controversy about the chronology of latest Pleistocene-early Holocene fluctuations. Early ^{14}C dates from Danger Cave strongly suggested that the level of Lake Bonneville had declined to within 34 m of the level of present Great Salt Lake (1,280 m) by 10-11,000 ^{14}C yr B.P., and had not risen higher since. Later, stratigraphic work by Morrison in the eastern Jordan Valley and ^{14}C dating by Broecker of materials from the Weber delta area indicated that Lake Bonneville had fallen to near the level of present Great Salt Lake by 10-12,000 ^{14}C yr B.P., but had then risen nearly to the Provo shoreline (1,465 m) between 8-10,000 ^{14}C yr B.P., before dropping back to near the level of present Great Salt Lake.

Evaluation of evidence from these localities supports the earlier interpretation from the Danger Cave data. Along Dry Creek, the sediments of the lower member of the Draper Formation, which Morrison believed were evidence of a post-10,000-yr-old high lake stand, are not of lacustrine origin. The poorly sorted, crudely bedded pebbly sand to silty sand is alluvium and colluvium of mid(?) Holocene age that partly filled the valley of Dry Creek and was later incised during the late(?) Holocene. At the locality near Ogden, the sediments from which disseminated organic matter and marl were dated at 9-10,000 ^{14}C yr B.P. form the upper 24 m of the Weber delta. The stratigraphic relationships of the sediments have been altered due to extensive landsliding. The dated materials may be greatly affected by contamination due to roots and ground-water discharge and be yielding ages that are too young. Sediment thickness and texture and stratigraphic position suggest that the sediments are related to an older and higher lake level than envisioned for the 8-10,000-yr-old stand.

2. There is presently confusion over the definition, correlation, and age of the Alpine Formation in the Bonneville basin that needs to be clarified if studies of recurrence of faulting are to have the necessary reliable age control. As mapped along the Wasatch Front by previous workers, the Alpine and Bonneville Formations (or Members) (deposited during the Alpine and Bonneville lake cycles) are not separated by a major unconformity and, therefore, may not have been deposited during different lake cycles. There is no evidence of a base level change with accompanying incision of deposits comparable to the change caused by the last disappearance of Lake Bonneville; there is also no clear evidence of a soil between the two formations. In many locations, the contact is a facies change in sediments of the same lake cycle; in other areas the contact is arbitrarily placed. Elsewhere workers have mapped Alpine and Bonneville deposits as more purely rock-stratigraphic units unrelated to lake history. In Little Valley at Promontory Point, the break between the Bonneville and Alpine Formations is characterized by the well developed Promontory Soil, indicating a major break in the pluvial lake history (probably equivalent to the last interglacial). Therefore the Alpine Formation as mapped at Little Valley probably was not deposited during the same cycle as the Alpine Formation (or Member) as mapped along the Wasatch Front; the "Alpine" Formation may be on the order of 140,000 yr at Little Valley vs. less than 50,000 yr along the Wasatch Front. The break that is probably equivalent to the Promontory Soil has been identified at several localities along the Wasatch Front and suggests that 1) the deposits of the last major lake cycle (Bonneville Formation) are very thick near major streams and that very little pre-Bonneville-lake-cycle deposits are exposed (previously Bonneville Formation deposits had been mapped as being quite thin and much less voluminous than the Alpine Formation, and 2) definition and usage of the term Alpine (Formation, lake cycle, etc.) need to be evaluated and clarified to prevent misuse and confusion. Furthermore, the limited exposure of pre-Bonneville-lake-cycle deposits along the Wasatch Front may deter using differential offset of Bonneville and Alpine Formations to infer long-term rates of tectonism.

3. Exploratory pits and trenches at Little Valley have exposed important stratigraphic sequences and relationships. Wood for ^{14}C dating has been collected that will hopefully yield information on lake fluctuations of early(?) to mid(?)-Wisconsin age. Other collected materials are being submitted for paleomagnetic and amino-acid measurments. A goal of the work in Little Valley is to use whatever methods possible to help correlate the poorly exposed sequences and individual exposures (especially those related to fault histories) along the Wasatch Front to the better exposed and the more datable sequence at Little Valley that also contains a longer record of lake history.

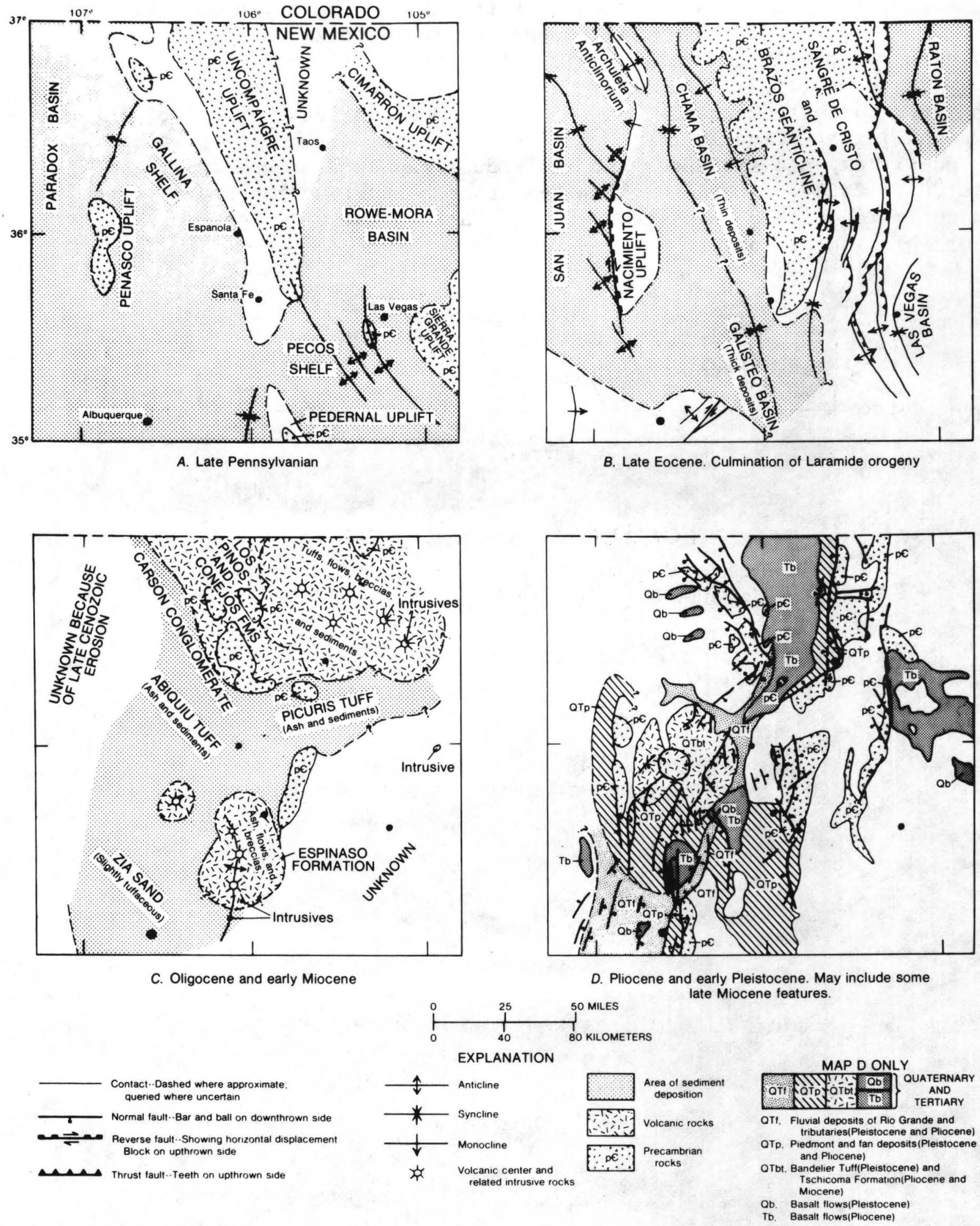
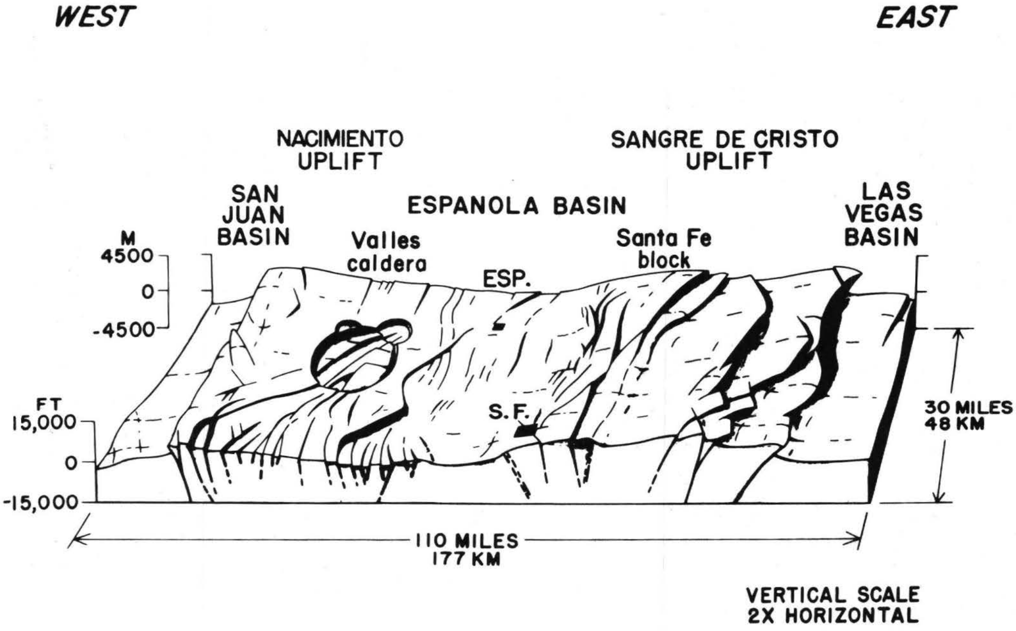


Fig. 1--Paleotectonic diagrams of north-central New Mexico showing (map D) principal Neogene faults of Rio Grande rift system (Baltz, 1978, p. 223)



PRECAMBRIAN BASEMENT

Fig. 2--Block diagram of Rio Grande rift and adjacent uplifts in latitudes of Santa Fe and Espanola, N. Mex.

NEVADA BUREAU OF MINES AND GEOLOGY
UNIVERSITY OF NEVADA, RENO

Semi-annual Technical Report Summary

Earthquake Hazard Maps Carson City, New Empire and South Lake Tahoe Quadrangles

January 1978 - June 1978

Dennis T. Trexler, Principal Investigator

The objective of this study is to develop earthquake hazard maps for three 7½-minute quadrangles which are undergoing accelerated growth. The quadrangles of interest are the Carson City, New Empire quadrangles; Nevada and the South Lake Tahoe quadrangle, California-Nevada. The resultant earthquake hazard maps will provide planning officials with a base from which prudent decisions on land use can be made.

During the first six months of this investigation, geotechnical data on the geologic units have been gathered from numerous sources. The engineering geology files maintained by Nevada Bureau of Mines and Geology was a primary source for most of the data.

At present we obtained data from 32 borings in the Carson City quadrangle, including data on shear wave velocity measurements for a State Office building located on younger alluvial valley fill material (Qal). The New Empire quadrangle poses a major problem in obtaining geotechnical data since large structures have not been built in this residential area east of Carson City. Seventeen boring logs for a dam site and sewer disposal facility in the northern portion of the South Lake Tahoe quadrangle are maintained in the Nevada Bureau of Mines and Geology engineering data file. Only data relative to Nevada are available from this source. We have made initial contact with engineering departments in the City of South Lake Tahoe and Eldorado County in California to access their files later this summer when we are making field seismic measurements.

Local geological engineering firms have been contacted and have provided data on several of the geologic units in the Carson City area.

During the remainder of the grant period shear-wave velocity measurements will be performed on the geologic units in the three quadrangles using the horizontal traction method. The shear-wave velocities will be combined with the unit bulk density and a rigidity coefficient will be determined.

Offshore Aeromagnetic Studies Related to the Charleston Earthquake Problem--A Feasibility Study

8-9730-02083

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Investigations

1. Study existing aeromagnetic data collected for the Atlantic continental margin oil and gas resource assessment program to make interpretrations of geologic structure which might be relevant to the Charleston Earthquake problem. The study area lies seaward of the coast from about 30°N to 34°N and about 30°W to 82°W.

2. Examine existing high resolution seismic profile data in the area to see if any evidence of shallow faulting or other features related to the earthquake are present.

Results

1. I previously reported that the 1:250,000 and 1:1,000,000 scale magnetic maps suggest a lineation which could be correlated with the projection of the Blake Spur fracture zone as mapped in the western Atlantic from magnetic and seismic data. Figure 1 shows the inferred trend in a portion of the published 50 nT contour interval magnetic map (Klitgord and Behrendt, 1977). The indicated lineation has a trend of about S 53° E where it crosses the coast about 20 km SW of Charleston (the flight line trend is S 39° E which introduces some confusion). The lineation truncates the East Coast Magnetic Anomaly (ECMA) at about 31°10' N, 77°40' W. At the southeast corner of figure 1 this trend projects into an offset in the Blake Spur anomaly and continues off the map on the trend shown by Schouten and Klitgord (1977). The lineation where mapped in the offshore area immediately adjacent to Charleston is not obvious at the scale and contours interval (50 nT) shown in figure 1. Portions of the 1:250,000 scale 2 nT contour interval map are shown in figures 2 and 3 as examples of the data used in drawing the line indicated in figure 1.

If the lineation represents the track and projection into the continent of the Blake Spur fracture zone, its relevance to the Charleston earthquake problem is not easily understood. The crust landward of the ECMA is continental and therefore any structure associated with the lineation shown in figure 1, predates the initial opening of the Atlantic and the trace of the transform fault marked by the oceanic

Blake Spur fracture zone. Certainly it would not be unusual for pre-existing continental structures or zones of weakness to localize a developing fracture zone at the time of initial rifting. Possibly the present day seismicity in the Charleston area is the result of the reactivation of the same zone of weakness.

2. Seismic profiling offshore Charleston, planned to cross the magnetic lineation discussed above, was postponed until spring 1979 because of ship schedules. Five ocean bottom seismographs were deployed offshore Charleston in a test array and during September and October 1978 for a period of about 8 weeks. No results are available as this is written.

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CAPE ROMAINE
CHARLESTON
EAST COAST MAGNETIC ANOMALY
BRUNSWICK ANOMALY
BLAKE SPUR ANOMALY
H.A.l.e
COST GE 1
DSDP 392
76°
32°
78°
30°
80°
0
25
50 Km
52000
51900
51800
51700
51600
51500
51400
51300
51200

Figure 1

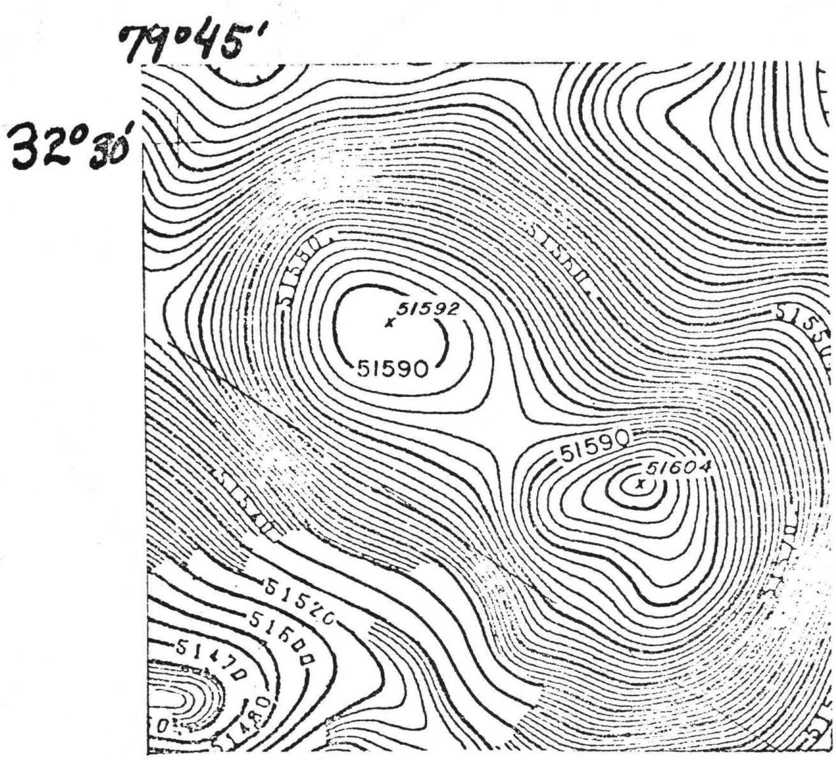

Figure 2

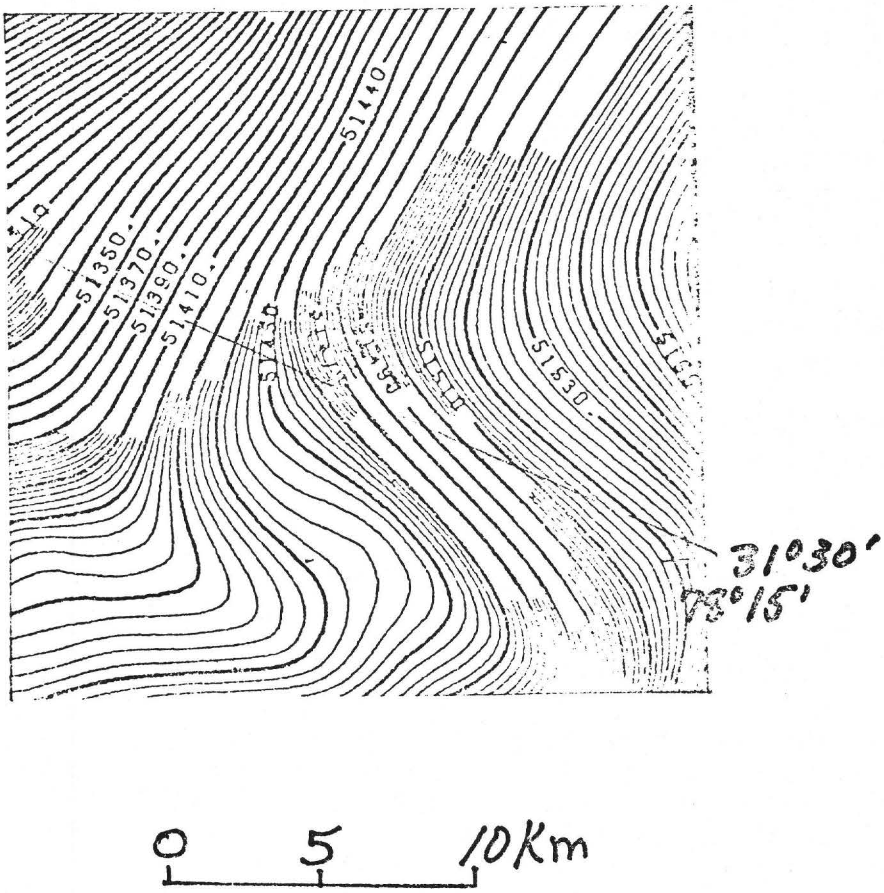

Figure 3

Late Tertiary and Quaternary Shoreline Datum Planes and Tectonic Deformation in the Southeastern United States

8-9590-00881

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Investigations

1. Continued field work, measured numerous sections and collected samples of Pliocene and Pleistocene deposits in Virginia, North Carolina and South Carolina, including study of many newly discovered localities.

2. Developed ostracode and molluscan biostratigraphic zonation for Pliocene and Pleistocene of Cape Fear Arch Region, North and South Carolina. Our biostratigraphic data, used in conjunction with paleoenvironmental analyses, were used to date shorelines along the coastal plain.

3. Began establishing paleomagnetic stratigraphy for coastal plain Pliocene and Pleistocene deposits by obtaining paleomagnetic determinations of numerous type localities and other outcrops from Joseph Liddicoat (Lamont-Doherty Geological Observatory).

4. Submitted samples to other Paleontology and Stratigraphy Branch personnel for analyses of planktic fauna and flora in an attempt to correlate onshore deposits with the deep sea biostratigraphic record.

5. Began analysis of sporomorph autoflorescence.

Results

1. Completed 1:1,000,000 map of age and distribution of Pliocene and Pleistocene shorelines from Virginia to northernmost Florida. This map is presently in branch review, intended for publication as a U.S. Geological Survey Miscellaneous Field Investigation.

2. From this shoreline map and the geographic distribution of Pleistocene marine deposits in the Atlantic Coastal Plain, we have determined that glacio-eustatic sea level fluctuations inferred from the deep sea isotopic, faunal and climatic record cannot fully explain the onshore distribution of marine deposits. Early (1.8-1.1 million yr BP) and middle (450,000-500,000 yr BP) Pleistocene marine deposits are absent from southern Virginia and middle Pleistocene deposits are presently unknown from northern North

Carolina, yet deposits of these ages are known from northern South Carolina. Certain regions of the coastal plain seem to have been emergent during warmer intervals of the Pleistocene when high stands of sea level are in evidence from the deep sea isotopic and planktic floral and faunal data, and from the onshore marine record in South Carolina. The tectonic implications of these results are as yet unknown.

3. Late Pleistocene marine deposits are present from northern Florida to Maryland and indicate sea levels during the last interglacial interval, and possibly the early Wisconsinan, at about 3.7 to 7.3 m. These values are comparable to estimates from numerous studies suggesting a high stand of a global sea level at about +6.0 m about 120,000 yr BP. No anomolous altitudes for these late Pleistocene deposits or their associated shorelines have been found, and hence there is as yet no strong evidence for post Sangamonian vertical displacement of late Pleistocene deposits and shorelines. Additional absolute dating, including uranium series dating of corals, is planned for better resolution in the correlation of late Pleistocene features and to determine if warping of shorelines has occurred.

Reports

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Seismotectonics of Northeastern United States

8-9950-02093

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Investigations

1. Initiated a review of the seismotectonics of the eastern United States with the immediate objective of helping to select seismic source areas for the outer continental shelf.

2. With the collaboration of O.H. Muller of Colgate University, initiated a gravity program in Pennsylvania: objectives are to achieve a better outline of major basement structures and to complete a gravity map of the State.

Results

1. O.H. Muller and two of his students (Jeff Trembley and Lisa LeClair) occupied about 1300 gravity stations in west-central Pennsylvania and began analysis of the data.

Tectonic History of Eastern Ozark Uplift

8-9530-01930

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Investigations

1. Logged cuttings and core from about 20,000 feet of hole drilled in and near the Newport, Arkansas, area (Phase 1).

2. Compiled structure contour maps of the Newport area.

3. Field checked and revised the 32 reconnaissance geologic maps (scale 1:24,000) of the Pocahontas, Arkansas, area (Phase 2).

Results

1. Previous fieldwork in the Newport, Arkansas, area had led to the discovery of outcrops of post-Paleozoic chert about 2 kilometers west of the edge of the Mississippi embayment and as much as 150 meters higher than the general level of the embayment. This summer a more fossiliferous outcrop of that chert was found. From it, B. W. Blackwelder and L. W. Ward of the Paleontology and Stratigraphy Branch of the USGS were able to identify one species of Midway (Paleocene) fossils. That paleontological evidence, supplemented by a great deal of field evidence, indicates that local uplifting took place in the Newport area sometime after the deposition of at least part of the Midway Group.

The number of individual post-Midway uplifts in the Newport area, their position, and their size was determined from additional subsurface data and from a reappraisal of field evidence. The Mobil Oil Corporation and the Arkansas Geological Commission made available cuttings and core from 25 stratigraphic test holes drilled in the southeastern part of the Newport area. Data from those holes indicate that a separate, somewhat smaller, probably post-Midway structure is buried by Cretaceous and younger sediments there. A third, much smaller uplift just southwest of Bald Knob, Arkansas, is postulated on the basis of field evidence.

The size of the three uplifts and their geographic relationship to the two-part Newport pluton and to the western edge of the Mississippi embayment are shown in figure 1. The outline of the uplifts was determined from geologic data; that of the pluton is based on geophysical data. No attempt was made to force the outlines to fit.

If one assumes that the uplifts are a result of the intrusion of magma and that the pluton is rather deeply buried dense and highly magnetic intrusive rock, three factors should be considered in evaluating whether the geographic proximity of the uplifts and the pluton is best explained as a direct, indirect, or fortuitous relationship:

1. Relative depth of intrusions--

The deepest hole drilled directly over both an uplift and the pluton is the Magnolia Petroleum Company - Roy Sturgis No. 1 well, sec. 30, T. 9 W., R. 3 W., Woodruff County, Arkansas (see figure 1). It cut no igneous rock and, at a total depth of 1.83 kilometers, reached only into the upper part of the Lower Ordovician. The Deardorf-Doggett No. 1 well was drilled at the eastern edge of the larger uplift and had similar results. Therefore, the relative depth of the top of the pluton versus that of probable igneous rock associated with the uplifts is unknown.

2. Nature of the igneous rock--

On the basis of geophysical evidence, the pluton is thought to be dense and highly magnetic rock. If any additional igneous rock is associated with the uplifts, it must be less dense and less magnetic. Otherwise it would have been identified more clearly by measurements of the gravity and magnetic intensities of the area.

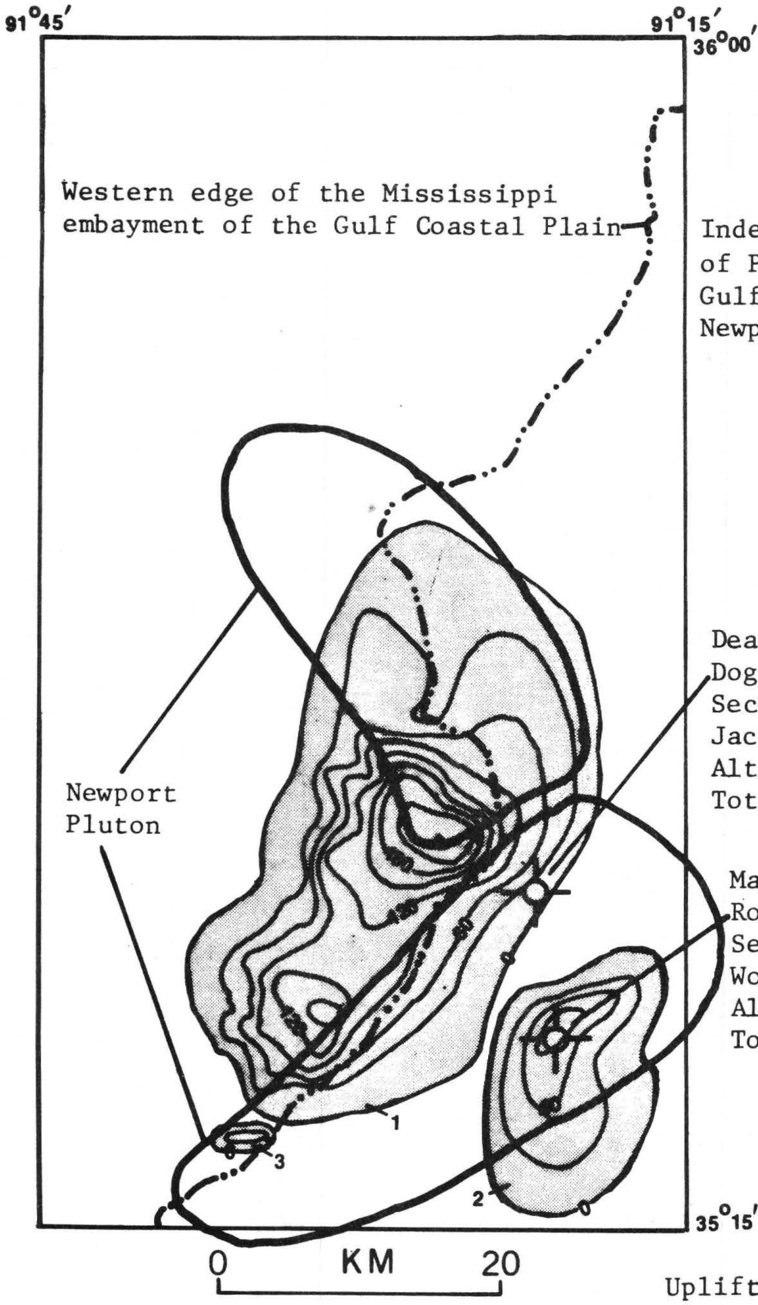
3. Age or ages of pluton and uplifts--

The age of the pluton is unknown. At least some of the uplifting took place within the past 50 million years, making it younger than any other yet dated major uplifting in the Mississippi embayment area. Probably all three of the uplifts are of post-Midway age.

The geographic proximity of the uplifts and the pluton suggests at least an indirect genetic relationship of the two. Field and subsurface evidence show no significant local uplifting away from the plutons of northeastern Arkansas. Probably the best estimate at this time is that the uplifts resulted from a secondary episode of the emplacement of the pluton. One fact is quite evident from field data--the larger of the three uplifts caused the abrupt offset or reentrant of the edge of the Mississippi embayment in the Newport area.

Reports

Glick, E. E., 1978, Structure of sediments above the Newport pluton of northeastern Arkansas (abs.): 1978 Midwest Meeting AGU, Program and Abstract, 1978, University of St. Louis, St. Louis, Missouri.



Index map of Arkansas showing area of Paleozoic outcrops (pattern), Gulf Coastal Plain (clear), Newport area (rectangle).

Contour interval 30 meters

Uplifts of probable post-Midway age

	Area	Volume
1.	766.0 km^2	46.3 km^3
2.	174.0 km^2	5.7 km^3
3.	7.3 km^2	0.16 km^3
Total	947.3 km^2	52.16 km^3

Figure 1. -- Map showing the location and size of uplifts of probable post-Midway age in the Newport, Arkansas area and their geographic relationship to the Newport pluton and to the western edge of the Mississippi embayment.

New Madrid Earthquake Study

8-9730-01035

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Investigations

1. Continued analyses of geophysically-inferred structures indicated in aeromagnetic data.

2. Determined approximate ages of igneous intrusions utilizing the total magnetic field intensity.

3. Extended aeromagnetic coverage in eastern Arkansas in order to delineate the southwest terminus of a proposed rift zone.

4. Carried out exploratory electromagnetic traverses to probe for conductive structures in the upper Mississippi embayment

Results

1. Geophysically-inferred structures in the upper Mississippi embayment include several mafic/ultramafic intrusive bodies as well as a parallel-sided depression of basement rocks which we interpret as a late Precambrian-early Paleozoic rift. A generated map of depths to magnetic basement indicates several kilometers of vertical movement has occurred along the rift's axis. Normal faulting is commonplace within extensional features such as rifts and may account for this large offset. Numerous magnetic gradients are observed trending normal to the rift's axis. The associated structures may be ancient faults formed during the rift's active periods. The strike of one of these structures coincides with a linear trend of concentrated seismicity. Because lateral offset in the rift's margins is also attributed to this structure, we propose that the corresponding feature is an active transverse shear zone.

2. Seven igneous intrusions located along the margins of the rift-like structure are characterized by circular aeromagnetic anomalies of high intensity. The associated sources are probably large shallow plutons consisting of highly magnetic mafic or ultramafic rocks. Approximate ages of these plutons have been determined by calculating for each a direction of remanent magnetization and comparing the corresponding paleomagnetic pole with the polar wandering path for North America. Remanent direction is obtained by first calculating the total magnetization direction from the moments of the anomaly and then

subtracting an induced component in the direction of the Earth's field. If appreciable care is taken in isolating the anomaly and in removing noise, this method for determining an age of a magnetic source can indicate a range of geological time periods spanning several million years, although it cannot reliably determine a specific period.

Using the described method of dating, attempts were made to compute the approximate ages of the seven intrusions emplaced along the rift's margins. No solutions were obtained for two of these intrusions due to the inability to remove the noise effects attributed to nearby sources. The analysis of one magnetic anomaly gives an early Paleozoic age, suggesting the emplacement of the associated pluton occurred during or soon after the rift's formation. On the other hand, age determinations for the four remaining intrusions indicate a major igneous event took place in post-middle Mesozoic time. Apparently, magma upwelling in the early stages of rifting resulted in igneous activity primarily within the rift zone. Later, the rift's border faults became enlarged due to subsidence and supplied a channel way for intrusive bodies in post-middle Mesozoic during reactivation of the rift.

Reports

Hildenbrand, T. G., 1978, Aproximate ages of igneous intrusions in the upper Mississippi embayment utilizing the total magnetic field anomalies (abs.): 4th Ann. AGU Midwest Mtg., Program and Abs., 1978, St. Louis University, St. Louis, Mo.

Engineering Geology of Metropolitan Boston, Massachusetts

8-9550-00637

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Investigations

1. Information from over 25,000 foundation borings from a 14-square mile area, including central Boston and parts of Cambridge and Brookline, has been collected and analyzed. From these data a series of subsurface maps, on a scale of 1:6000, is being prepared which, when used together, provides a three-dimentional picture of the geology. There will be seven maps: one for each of the five most important stratigraphic materials units (Holocene estuarine and freshwater deposits, outwash sands and gravels, glacial clays with interbedded silt and fine sand, till and older outwash, and bedrock), and two additional maps, one showing the topography of the bedrock surface and another showing the location of all borings. With each map will be a text, a table of physical-properties data, and cross sections.

2. Surficial geology of eight 7 1/2-minute quadrangles (Lexington, Newton, Boston North, Boston South, Lynn, Hull, Marblehead South, Nantasket) has been mapped. These maps include submarine geology in the submerged portions.

3. Bedrock geology of the above eight quadrangles has been mapped.

4. Field investigations are essentially completed. The project is in report-writing phase.

Results

Bedrock maps of Boston North, Boston South, and Newton quadrangles 90 percent compiled. These show a dense network of faults in the Boston Basin as well as in the sukrrounding crystalline terrain. In the central and eastern part of the Basin, the major faults are east-west, curving to east-northeast to the east. These faults cut up the Basin into seven long slices, each characterized by specific stratigraphy and structure. Cutting east-west faults are long north-south faults which are most important in the west. Also the basin is broken by a mosaic of lesser faults, most of which preceded east-west faulting.

Many faults are marked by diabase dikes, or contain well-lithified cataclasite, difficult to differentiate from country rock; or by a zone of intense soft rock alteration; or else there is a broad zone of shearing rather than a single clean, sharp ruptukre. It is because of these and other reasons it has taken so long to recognize fauklting in these rocks which have been studied for well over a century.

Reports

None.

Northeastern U. S. Seismicity and Tectonics

9510-02388

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Investigations

1. Field investigation of Ramapo Fault in New York and New Jersey to determine location and attitude of faults possibly associated with recent seismicity.

2. Detailed examination of bedrock and surficial deposits in the vicinity of June 1978 earthquake epicenter south of Mahwah, N. J. spatially associated with Ramapo Fault.

3. Core drilling of hanging wall and foot wall blocks of Ramapo Fault at selected localities to recover samples of fault contact and cataclastic rocks for purpose of assessing evidence for current reactivation.

4. Reconnaissance study of offset glacial striae and polished surfaces on faults previously reported by Oliver to evaluate tectonic framework associated with these features.

Results

1. Cataclastic rocks and structural data indicate rocks of the foot wall block of the Ramapo fault in New Jersey and New York have a polygenetic fabric with the most recent movement being oblique-normal slip on southeast dipping faults. No evidence was found for reverse movement expected to have formed from the current NW-SE compression deduced from the focal plane solutions of Aggarwal and Sykes for Ramapo associated earthquakes.

2. An instrumentally recorded earthquake of approximately magnitude 3 was recorded June 30, 1978 by the Lamont seismic network with an epicenter close to the trace of the Ramapo fault near Mahwah, New Jersey. Field investigations in the area of greatest felt reports on July 1 and 2 with Lamont scientists failed to reveal any clear evidence of surface disruption. Mapping in the vicinity of the epicenter indicate a greater complexity for Ramapo fault here than elsewhere owing to N-S and NNW cross faults. This structural complexity appears to be spatially related to a zone of more active seismicity that extends from Mahwah to Pompton Plains,New Jersey.

3. Continuous NX core drilling of the poorly exposed Ramapo fault north of Suffern, New York has penetrated the fault contact in two holes in a line normal to the regional northeast strike of the fault. The fault between Triassic-Jurassic (?) lava flows and Precambrian gneiss of the foot wall dips 60° southeast. Cataclastic rocks of the fault zone have been recovered and total recovery of the critical fault contacts in the two holes have been obtained. Detailed mineralogic and structural studies of the core will evaluate the evidence for current reactivation of the fault. The 60° southeast dip agrees well with the inclination of the potential fault surfaces identified by the focal-plane solutions of Aggarwal and Sykes for Ramapo associated earthquakes, but to date the actual dip of the Ramapo fault has been unknown. Additional coring at other sites along the Ramapo are now in progress.

4. Offset glacial striae in southeastern New York reported by Oliver appear to occur near late brittle faults of possible Mesozoic age with cataclastic fabrics similar to the Ramapo (Triassic border) fault based on preliminary studies of some of Oliver's best localities. Further study of these features and their possible association with regionally important fracture patterns is being undertaken.

Mississippi Valley Seismotectonics

8-9950-01504

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Investigations

1. Continued geomorphic investigations of Reelfoot Lake vicinity, northwestern Tennessee, using air-photo and map analysis and field investigations.

2. Continued mapping and investigating late Pleistocene fluviatile terraces in the upper Mississippi embayment in an effort to determine recency of movement on the Ste. Genevieve fault and to delineate patterns of Holocene surface deformation. Investigations included 1) the determination of terrace surface elevations, using an altimeter; 2) paleomagnetic sampling (with G. Shoemaker and J. Gassaway) of terrace sediments for stratigraphic correlation purposes; and 3) reconstruction of terrace levels, using trend-surface analysis.

3. In cooperation with M. Zoback, began drilling a test well 5 miles east of Portageville, Mo., 1 mile (1.6 km) west of the Mississippi River in the Missouri bootheel for the principal purpose of obtaining a subsurface stress measurement utilizing the hydrofracturing technique. The test well will also yield stratigraphic and paleontologic information on the Paleozoic, upper Mesozoic, and Cenozoic rocks in an area where the stratigraphic sequence is poorly understood. The test well will be available for future water, heat flow, velocity, and seismographic studies.

4. With S. Obermeier, continued field investigations into the factors that control the occurrence and characteristics of earthquake-induced liquefaction phenomena in the Mississippi embayment.

5. Continued compilation of published and unpublished C-14 age data for the Mississippi embayment.

Results

1. One of two Indian mounds located on the northwestern shoreline of Reelfoot Lake was found to have undergone severe erosion and slumping by the corroding action of lake waves. The erosion resulted in a reduction in the size of the mound by about 50 percent. This information, together with an analysis of landform patterns and structural features in the vicinity, lead to the tentative conclusion that Reelfoot Lake was substantially enlarged during the New Madrid earthquake of 1811-12. Parts of the lake, however, formed much earlier as a series of coalescing oxbow lakes in old abandoned Mississippi River channels. The enlargement appears to have been caused by 2 to 3 ft. of earthquake-induced compaction of the old river channel clays; no evidence of subsidence by faulting has been found.

2. To date, no evidence of faults offsetting Pleistocene or Holocene terrace surfaces has been detected. Though most outcrops of the late Wisconsinan Festus Terrace have been found to be too strongly oxidized and iron stained to be suitable for paleomagnetic analysis, several areas of well-exposed unoxidized terrace outcrops were sampled. Analysis of the sample map may aid in correlating isolated Festus Terrace remnants and in establishing a record of paleomagnetic secular variation for the late Wisconsin in the Mississippi Valley.

3. Drillers' logs compiled from samples collected from the first 1,500 ft (475 m) of the New Madrid test well being drilled near Portageville, Mo., and geophysical logs run on the same interval have resulted in a detailed description and identification of Tertiary sediment sequences encountered in the hole. Tertiary formations that were identified and named in the U.S. Geological Survey Fort Pillow test well (located at Fort Pillow, Tenn., 53 miles (85 km) south of the New Madrid test well) were recognized in the New Madrid well. These units are the Eocene Jackson Formation, the Eocene Claiborne Group (composed of the Cockfield Formation, the Cook Mountain Formation, and the Memphis Sand), the Eocene Wilcox Group (composed of the Flour Island and Fort Pillow Formations), and the Paleocene Porters Creek Clay. Identification of these units represents the first instance where the Claiborne Group has been formally recognized in the Mississippi embayment sediments of Missouri. Until now, the Claiborne-Wilcox interval was mapped solely as Wilcox (with the local names Ackerman and Holly Springs being applied). The soft, incompetent nature of the Jackson, Claiborne, and Wilcox sediments frustrated efforts to core the clayey parts of these units. Sediment samples were collected and split for USGS, Office of Earthquake Studies, USGS, Branch of Paleontology and Stratigraphy, the Missouri Geological Survey, and the Geophysics Department of St. Louis University. To date, no significant occurrences of lignite, hydrocarbons, or any other material of economic significance has been encountered.

4. In an investigation of the distribution of liquefaction features in the Mississippi Valley north of Memphis, Tenn., no sand blows were identified on Sikeston Ridge--a braided stream terrace situated at and extending north of New Madrid, Mo. Sand blows, however, were identified in the modern flood plain east and west of the southern half of the ridge. It was found that hand augering could be used to differentiate sand blows from sandy deposits of river point bars.

5. Continued geomorphic analysis of maps of the Reelfoot scarp trench in northwestern Tennessee reveals that there is a strong genetic association between sand blow dikes and faults exposed in the trench. Sand dikes are generally injected along faults and are evenly distributed within areas where faulting occurs. Because the sediments of the trench are extremely soft and incompetent, there is no strength advantage for a dike to be injected along a preexisting fault plane; such fault planes would probably not act as zones of weakness to the upward-mobilized sand. The inference, therefore, is that the sand dikes and faults formed simultaneously during strong earthquakes. Thus the 0.5-m wide zone of eastward-dipping surficial normal faults located at the base of Reelfoot scarp (and which is underlain at depth by faults) is believed to be the only surficial tectonic fault known to be associated with upper Mississippi embayment earthquakes.

Reports

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Russ, D. P., Late Holocene surface faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee: Geological Society of America Bulletin.

Northeast Tectonics and Geophysics

8-9730-00364

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Investigations

1. Compilation of available gravity data for the Northeast. Publication of contoured gravity maps at various scales suitable for regional and local studies.

2. Compilation and digitization of available aeromagnetic data from the Northeast, and collection of additional data from areas of interest. Publication of contoured maps and digitized data sets.

3. Collection of gravity, magnetic and other geophysical data in areas of tectonic or seismic significance.

4. Interpretation of regional geophysical anomalies and their relation to tectonic features and the plate tectonic history of the region.

5. Modelling and interpretation of local geophysical anomalies to test specific hypotheses for the origin of seismicity.

Results

1. A computer file of approximately 50,000 gravity stations in the Northeast is nearly complete, and machine contoured maps can be generated at any scale or projection. Gravity maps of the Boston 1^{o} by 2^{o} sheet and the state of Connecticut have been put on open file.

2. A contract has been let out for additional aeromagnetic coverage in the Gulf of Maine over the offshore extension of the Clinton-Newbury and Bloody Bluff faults. Available aeromagnetic data in the vicinity of Anna, Ohio has been digitized.

3. Reconnaissance sparker lines were run offshore from Cape Ann and Newburyport, Massachusetts in cooperation with U.S.G.S. Branch of Marine Geology at Woods Hole. Observed differences in basement topography may be useful in extrapolating onshore geology offshore.

Reports

Bothner, W. A., 1978, Preliminary complete Bouguer gravity map of the Boston $1^{\circ} \times 2^{\circ}$ quadrangle, Massachusetts: U.S. Geological Survey Open File Report 78-810, scale 1:250,000.

Bothner, W. A., and Brace, R. D., 1978, Principal facts for gravity stations in the State of Connecticut: U.S. Geological Survey Open File Report 78-804.

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Radon Fluctuations in the Northern Mississippi Embayment

14-08-0001-G-488

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Report Summary

In February, 1977, a 10-station network of radon monitoring stations was established in the northwest-trending segment of the New Madrid Seismic Zone, in the northern Mississippi Embayment. Weekly monitoring of these stations, using solid state nuclear track detectors to infer radon levels from alpha particle activity, revealed substantial variations of radon levels in time. Comparisons of the radon flux to concurrent variations in temperature, rainfall, barometric pressure differentials, earth-tide differentials, water levels, and seismicity were quantitatively assessed through the use of cross-correlation techniques.

The results indicated statistically significant relationships existing between radon levels and the factors of seismicity, barometric pressure, and water levels. Large excursions in weekly barometric pressure levels, and increasing water levels both appeared to escalate radon levels. A seasonal variation in radon levels was also observed, but did not appear to be temperature induced. Pressure and temperature data were taken from the weather service in Dyersburg, Tennessee. Water level data for a deep well in the seismic zone were provided by Brian Mitchell of the Earth and Atmospheric Sciences Department at Saint Louis University.

No correlation was found between rainfall and radon levels. A possible subtle influence on radon levels by the bi-weekly earth-tide variation was suggested by cross-correlation results. Earth-tide data were reduced from the tidal-gravimeter information provided by Saint Louis University.

The seismic parameters considered were frequency of events which occurred in each weekly period and the total amplitude of ground displacement each week. The correlation results disclosed that radon levels increase significantly approximately 4 to 6 weeks before periods of peak seismic activity, as defined by the number of events, and decline just prior to periods of increased ground displacement. In general, radon levels remain low or decline further for 1 to 2 weeks after such periods. Visual analysis of the radon and seismicity fluctuations substantiated the cross-correlation interpretations.

The close correspondence between general trends in periods of peak radon emanation and peak seismic activity is seen in the compar-

ison of smoothed radon and seismic data (Figure 1A). The accompanying cross-correlation (Figure 1B) shows the significant positive correlation between these two factors, as well as a gradual decline and regular spacing of peaks in the correlation coefficient. This may be reflecting the periodic tendencies shown by both radon and seismicity fluctuations. Seismic data were taken from the Southeast Missouri Regional Seismic Network Bulletins (Stauder et al., 1977-78).

It is suggested that periods of high radon emanation are related to strain accrual which precedes periods of peak seismicity. Perhaps deformation of the thick Mississippi Embayment and alluvial sediments by tectonic stresses causes increased surface radon abundance (Steele, 1978). A similar mechanism is suggested by King (1978) as a possible mechanism for temporal radon flux in the San Andreas region.

Analysis of the spatial distribution of radon was achieved by monitoring a network of 62 stations which encompassed the seismic zone, as well as adjacent areas which were relatively aseismic. Maps of the radon distribution for each month of the period from June, 1977, through June, 1978, revealed a characteristic pattern of anomalous radon emanation coinciding with, and closely paralleling the seismic trend in a generally linear configuration (Figure 2). The most prominent zone of intense radon emanation was located in the area of most frequent epicenter occurrence.

Suggested possible mechanisms for the spatial radon anomalies in the seismic zone are: 1) greater ease of radon emanation due to subsurface faults, 2) increased uranium and/or radon due to increased fluid circulation in subsurface faults.

Three small zones of high radon concentration were observed outside of the zone of intense seismicity. These areas appear to coincide with the edges of igneous intrusive bodies located through gravity aeromagnetic surveys by Hildenbrand and others (1978). It is suggested that uranium enrichment resulting from fluid convection in the faulted peripheral zones of the intrusives may be a source of anomalous radon levels in these areas.

Reports

Steele, Sheila, 1978, Spatial and temporal radon variation in the New Madrid Seismic Zone, unpublished masters thesis, Southern Illinois University, 107 p.

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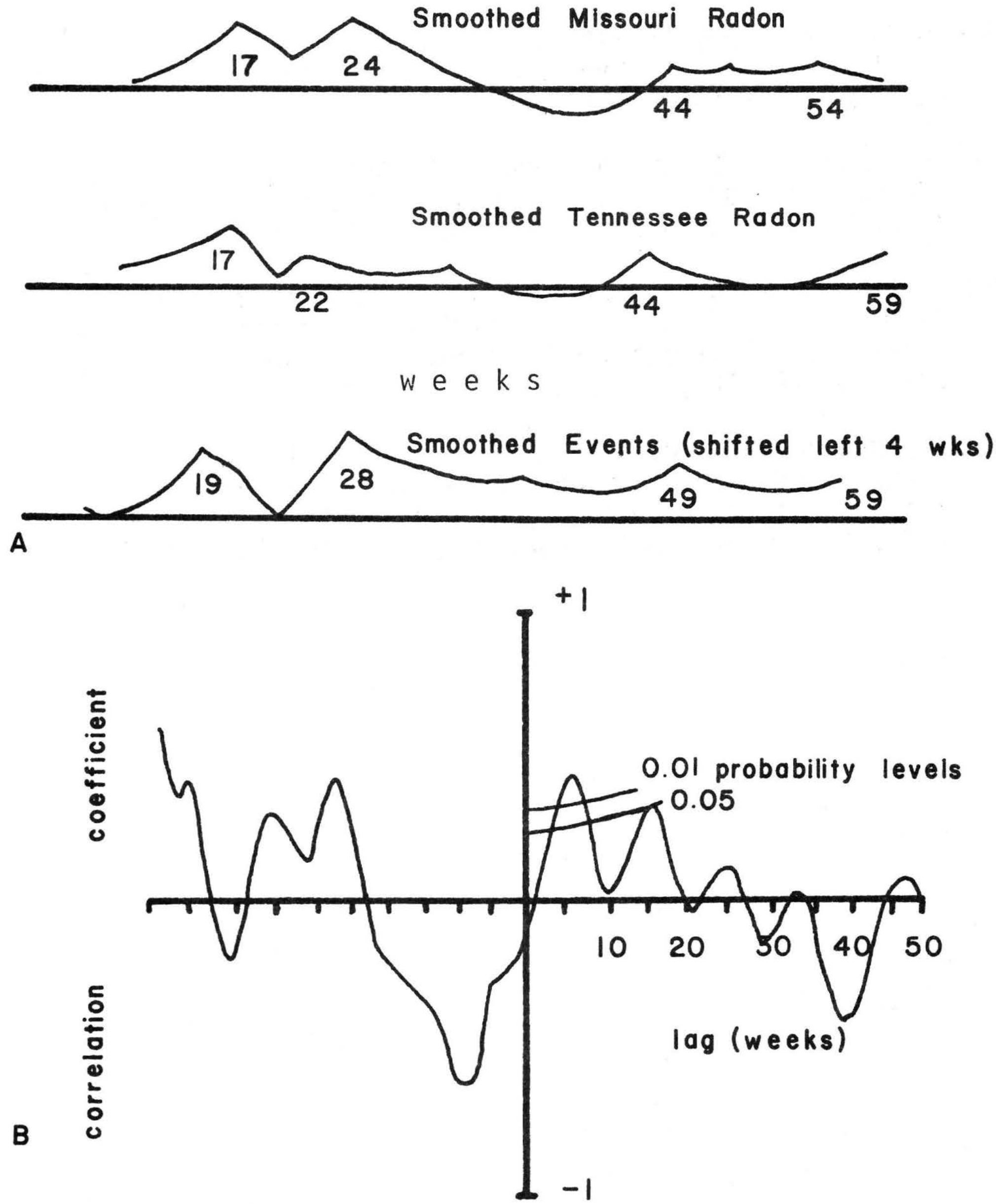

Figure 1. Time series and cross-correlation of smoothed seismic and radon data. Horizontal lines on time series are 0 mean lines for unsmoothed data (from Steele, 1978).

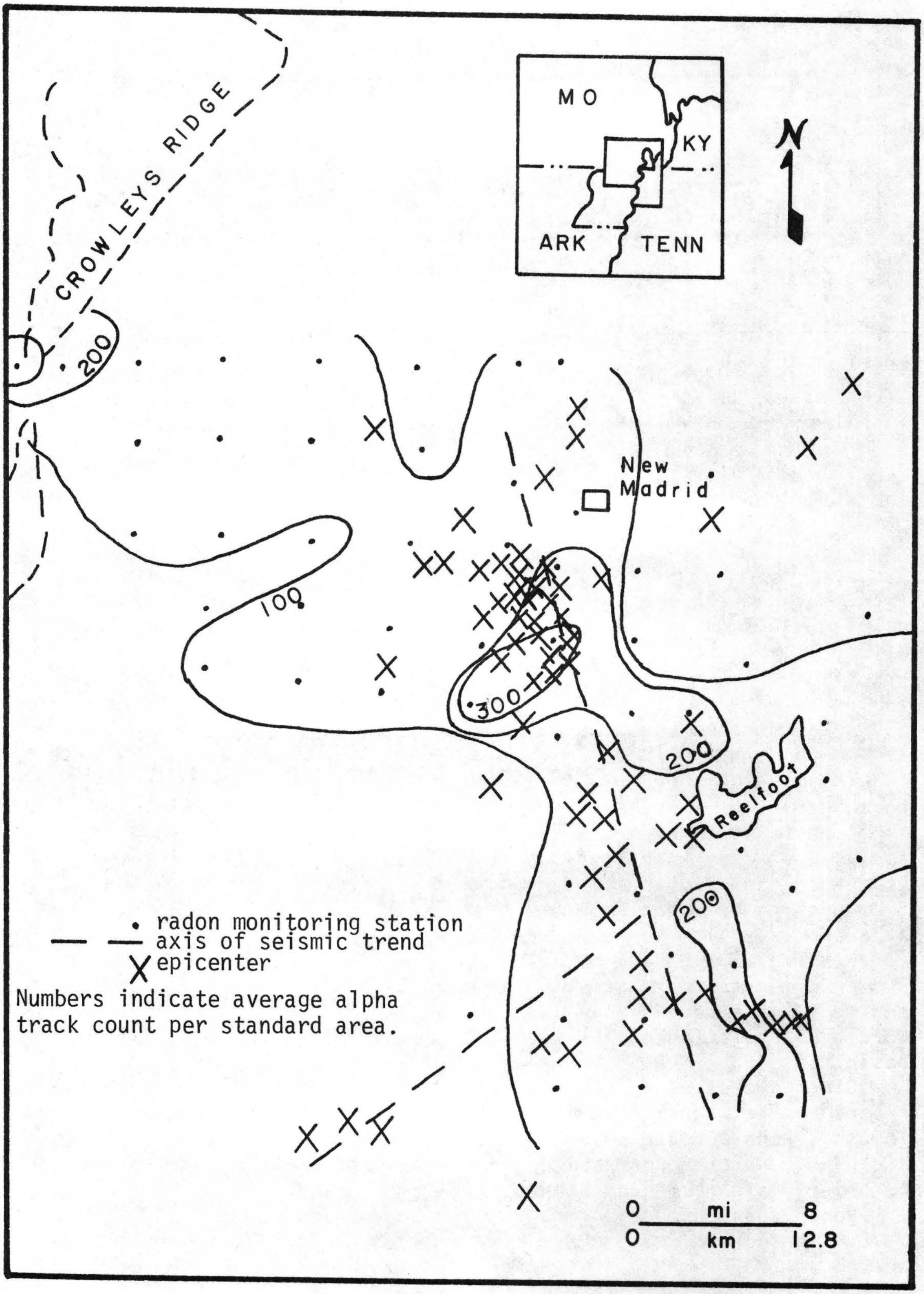

Figure 2. Thirteen-month-average radon levels in the New Madrid Seismic Zone (from Steele, 1978).

Norumbega Fault Zone, Maine

8-9510-02165

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Investigations

1. Examined the bedrock geology in a region between Great Pond and Grand Lake Stream, Maine in order to determine the nature and magnitude of faulting along the Norumbega Fault Zone (See Figure 1).

2. Examined glacial landforms, deposits, and glacially polished surfaces for evidence of Holocene activity related to the Norumbega Fault Zone.

Results

1. The Norumbega Fault Zone is a 3 to 4 km wide zone containing three or more strike-slip faults extending from Winterport to Grand Lake Stream, Maine. According to Larrabee (1965) and Ludman (1978), the fault zone extends east of Grant Lake Stream and merges with the Fredericton Fault in central New Brunswick. Bedrock mapping during June, July, and August of 1978 demonstrated the continuity of the faults within the zone, as well as the zone itself.

The most common formation that outcrops in the region is the Vassalboro Formation, a calcareous pelite with interbedded sulfidic pelite. Away from the fault zone, the Vassalboro Formation exhibits graded beds, small scale scour and fill, and contorted beds characteristic of a turbidite. Ruitenberg and Ludman (1978) consider the Flume Ridge Formation of New Brunswick to be correlative with the Kellyland Formation of Eastern Maine (Larrabee, 1965). Wones (1976) considered the Vassalboro Formation to be correlative with the Bucksport Formation (Wing, 1957). Mapping this summer demonstrated that all four units are correlative and represent the sediments accumulated in a large basin of Siluro-Devonian age. The Norumbega Fault Zones lies within and parallel to the long axis of that basin.

Older gneisses and schists occur along and within the fault zone in the region between Winterport and Great Pond, Maine. Rocks within the Wabassus Lake Quadrangle assigned a Cambro-Ordivician age by Larrabee (1965) are highly deformed and silicified rocks of the Vassalboro Formation that occur only along the fault zone.

Post-Vassalboro conglomerates and sandstones occur within the fault zone. The conglomerates have red sandstone matrices, and contain poorly sorted, subrounded clasts of quartz, feldspar, shales, and medium-grained granitic rocks. The conglomerates are well indurated, but not strongly cleaved as is the Vassalboro Formation. They are roughly similar to rocks of the Perry Formation (Late Devonian), the Horton Formation (Mississippian), the Canso Formation (Pennsylvanian) of the Newark Gp.(Triassic & Jurassic) No fossiliferous material has been recovered from these rocks. The conglomerates and sandstones dip steeply into the faults bounding their outcrop area. This implies vertical motions of at least several hundred meters along the faults within the zone.

Four large plutons (300 km^2 in area) are truncated by the fault zone. All are coarse-grained, are rich in K-feldspar, and have biotite as the dominant accessory. Within the fault zone, blocks of coarse-grained granitic rocks have been deformed to an augen gneiss. This makes it very difficult, in the field, to correlate these blocks with the large plutons. Confined to separate fault-bounded blocks within the fault zone are medium-grained granite and syenite. No rocks that are correlative with either of these latter types have been observed north or south of the fault zone.

The most satisfactory reconstruction of the fault zone requires 10-20 km of right lateral motion, accompanied by several hundred meters of vertical motion. This reconstruction leaves the easternmost of the large plutons without its northern half. Petrographic studies will be required to confirm this reconstruction.

Steeply plunging minor folds, offsets of minor fractures, and slickensides all indicate that the fault motions that trend N45E-N60E are dextral. Minor fractures that trend N20W and N60W all show sinistral offsets of 1 mm to 5 cm. This pattern indicates a principle compressive stress that is subhorizontal and oriented E-W. The NW movements offset the NE features. If these NW offsets represent readjustments of accumulated stresses after the major faulting, the Norumbega Fault Zone is probably inactive.

Preliminary examination in thin section of rocks adjacent to the fault reveals that much of the deformation is brittle fracture accompanied by intergranular flow. Quartz "ribbons" are characteristic of the feldspathic rocks. Thin bands of mylonite frequently have a glassy appearance. Deformation within the Vassalboro formation consists of disaggregated, milled and ribboned quartz from earlier quartz veins, accompanied by the transposition of carbonate-rich beds parallel to the faults.

2. Woodrow B. Thompson of the Maine Geological Survey investigated glacial deposits and landforms in the vicinity of the fault zone for evidence of Holocene activity. Such features are: 1) glacially striated or polished bedrock outcrops, 2) exposures of the bedrock-overburden interface, 3) internal exposures of stratified glacial sediments, 4) internal exposures of postglacial alluvium, 5) glacial and postglacial landforms such as esker ridges or terrace surfaces, 6) raised beaches or recent scarps resulting from recent faulting.

Well-stratified surficial sediments are absent or poorly exposed over much of the area. Many of the ice-contact deposits are stratified, but the bedding has been deformed adjacent to melting ice. An oxidation boundary within the Presumpscot Formation on the east bank of the Penobscot River did not reveal any evidence of faulting.

The Norumbega Fault zone has a clear expression on topographic maps, aerial photographs, and Landsat imagery. Examination of maps and aerial photographs did not reveal large-scale faulting of eskers or other landforms. The observed deflections of streams and esker segments can be best explained by differential erosion along the preexisting fault traces.

200 outcrops were examined for post glacial faulting of the rock surface. Six exhibited definite postglacial faulting. All the observed exposures are in the Vassalboro Formation and exhibit the following features:

a) Most are bedding plane faults.
b) The faults have vertical dips.
c) None was observed to extend more than a few meters.
d) There is no consistent direction in which the scarps face.
e) There is no apparent relationship between the faults and the topography of the outcrop.
f) The faults are tight with little or no open space along the fault planes.
g) The amount of offset is between 1.5 and 30 mm. No lateral displacements were observed.

Oliver and others (1970) proposed that such faulting could be explained by slumping, frostheaving, regional stress, rock expansion, unloading. The orientation of the faults and the outcrop surface discount slumping and mass-wasting. Frost heaving may have contributed to localities where minature horsts are observed, but those where all the fault scarps face in the same direction must be due to another cause. There is no indication of alteration of the Vassalboro that would lead to expansion. Uplift related to the unloading of glacial ice is the most probable cause.

The lack of lateral offsets in the small postglacial faults, and the fact that NW joints and faults offset the NE trending deformation surfaces in the fault zone leads to the conclusion that the Norumbega Fault Zone has been inactive during the Holocene.

Reports

Thompson, W.B., 1978, Postglacial Faulting in the Vicinity of the Norumbega Fault Zone, Maine: Open File Report, October 1978, Maine Geological Survey. 21 pages.

Thompson, W.B., in press, Postglacial Faulting along the Norumbega Fault Zone, Eastern Maine: Geol. Soc. Amer. Abstracts with Programs (Northeast Section)

Wones, D.R., and Thompson, W.B., in press, The Norumbega Fault Zone: A Major Regional Structure in Central Eastern Maine: Geol. Soc. Amer. Programs with Abstracts: (Northeast Section Meeting)

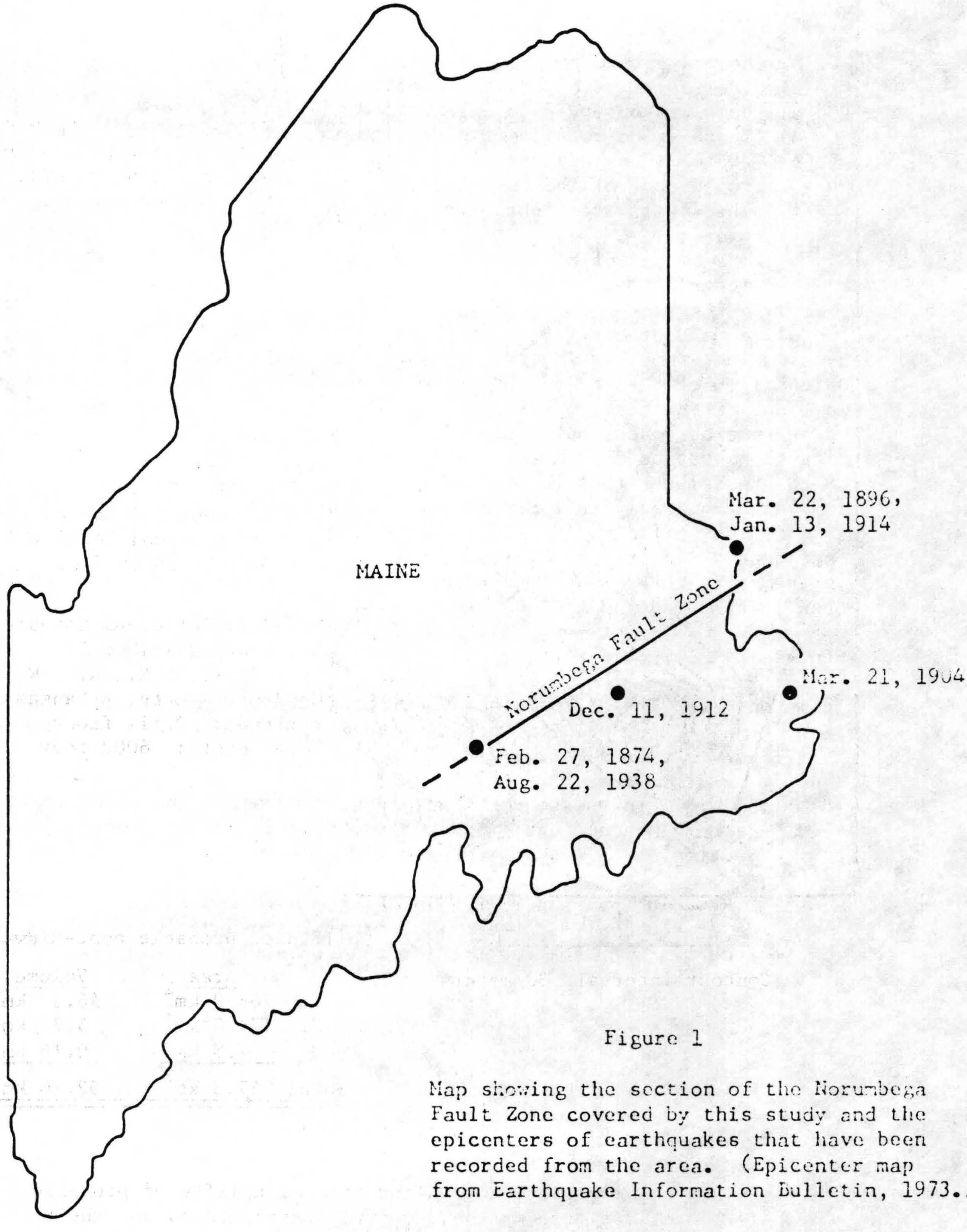
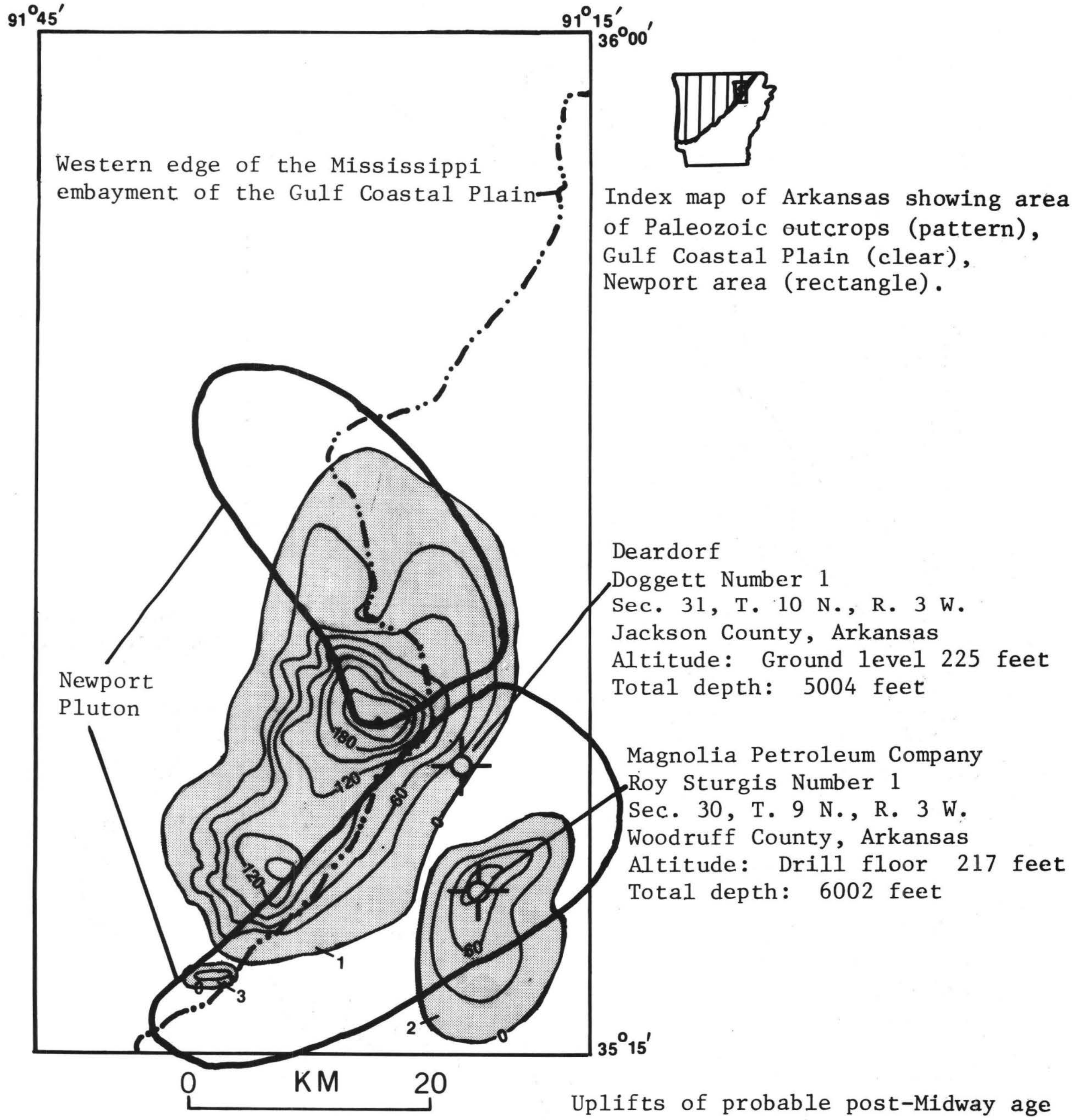


Figure 1

Map showing the section of the Norumbega Fault Zone covered by this study and the epicenters of earthquakes that have been recorded from the area. (Epicenter map from Earthquake Information Bulletin, 1973.)



Contour interval 30 meters

Uplifts of probable post-Midway age

	Area	Volume
1.	766.0 km^2	46.3 km^3
2.	174.0 km^2	5.7 km^3
3.	7.3 km^2	0.16 km^3
Total	947.3 km^2	52.16 km^3

Figure 1. -- Map showing the location and size of uplifts of probable post-Midway age in the Newport, Arkansas area and their geographic relationship to the Newport pluton and to the western edge of the Mississippi embayment.

Neotectonic Synthesis of U.S.

8-9540-02191

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Investigations

The objective of the project is to design and compile a small-scale neotectonic map of the conterminous United States from existing geologic data with the help of various regional experts.

The work is proceeding in two parts: project study and compilation, and non-project compilation by regional experts. A literature search is underway to assure consideration of map content, cartography, and methods of neotectonic synthesis represented in the world literature, and to amass a basic bibliography on late Cenozoic deformation in the conterminous U.S. Tentative areal priorities are, in decreasing order, 1) California, western Washington, and western Utah, 2) the west (west of long. 105°W), 3) a transect between the east and west coasts approximately along lat. 34° - 38°N, and 4) the balance of the east. In addition to work on the form and content of a 1:5,000,000-scale map of the U.S., project personnel will work on pilot compilations of diverse regions selected from items 1 and 3 in the priority list.

Sufficient project funds are anticipated in FY 79 to permit a formal request for proposals from regional experts for modest support to compile information already in hand. The resulting regional maps at intermediate scale (1:1,000,000±) will be published by the Geological Survey, and will serve as key sources in compiling the U.S. map.

Collaborative Dating

9-9740-00374
9-9740-00377
9-9740-00379
9-9740-00389
9-9740-01568

C. M. Bunker, B. R. Doe, M. Rubin,
M. A. Lanphere, C. W. Naeser, and S. Robinson

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Denver, CO. 80225
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Investigations

The age of faulting and fault recurrence are recognized to be important to assessing future earthquake hazards. The Branch of Isotope Geology is participating with various field geologists in determining the age of faulting by various standard techniques. The dating techniques are radiocarbon, potassium-argon, and fission track. In addition, we will be working on development of new dating methods such as thermoluminescence dating of soil carbonate and non-destructive techniques by high resolution gamma-ray spectrometry--ionium dating of volcanic rocks, lead-210 and radium dating of soils.

Results

The ages determined by standard techniques are reported in the individual reports of the field geologists working on neotectonics and they will not be repeated here.

STUDY OF EARTHQUAKE RECURRENCE INTERVALS ON THE WASATCH FAULT, UTAH

U.S.G.S. Contract No. 14-08-0001-16827

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Summary of Interim Technical Report, September, 1978

Purpose of Study

The Wasatch fault is an active intraplate fault that extends more than 370 km from Gunnison, Utah to Malad City, Idaho. The fault exhibits almost continuous geomorphic expression of late Quaternary faulting and displaces Pleistocene lacustrine sediments deposited by Lake Bonneville and its predecessors, and late Pleistocene and Holocene alluvial and colluvial sediments. However, no earthquake of a magnitude greater than 6 is known to have occurred along the Wasatch fault since the region was settled in 1847. Investigations conducted in 1975 by Woodward-Clyde Consultants (Contract No. 14-08-001-14567) identified six sites that have a high probability of yielding information regarding recurrence of surface faulting along the Wasatch fault. Detailed geologic mapping and subsurface investigations are being conducted at two of these sites, the Kaysville site (32 km north of the Salt Lake City) and the Hobble Creek site (28 km southeast of Provo), to measure fault displacements in strata that can be dated or correlated with dated units. These data are used to estimate the frequency of recurrence of moderate to large earthquakes associated with surface faulting events along the Wasatch fault.

Field Investigations

Field investigations were conducted at the Kaysville site during June, 1978. These investigations included: a) photointerpretation using 1:12,000 low-sun-angle black-and-white aerial photographs; b) detailed surface mapping of faults and late Quaternary stratigraphic units at a scale of 1:6,000; c) topographic profiling of fault scarps; and d) excavation of test pits and exploratory trenches. Seven trenches totaling 189 meters in length and varying in depth from 2 to 6 meters were excavated. Trenches were logged in detail at a scale of 5 cm = 1 m.

Results

The following conclusions and observations are based on the geologic mapping and on stratigraphic and structural relationships observed in colluvial and sag fill deposits exposed in trenches excavated across the main Wasatch fault scarp and an associated graben at the Kaysville site:

1. Cumulative vertical tectonic displacement of the unconformity between Alpine-Bonneville lake sediments and post-Provo alluvial fan deposits is 10 to 11 meters down to the west across the main fault scarp and graben. The unconformity has a maximum age of 9000 to 12,000 years. The post-Provo alluvial fan surface, estimated to be 6000 years old, is displaced approximately the same amount.

2. At least three episodes of surface faulting that have been associated with large earthquakes have occurred along this trace of the fault in post-Provo time. The oldest recognized event(s) tilted the post-Provo alluvial fans, resulting in the formation of a sag that was subsequently filled by a bedded sequence of sand, silt, and gravel. The next event tilted these deposits toward the main fault, and the sag filled with additional pond, alluvial and colluvial deposits. The most recent event produced a graben but did not produce tilting toward the range.

3. Stratigraphic relationships suggest that the most recent event may have occurred within the past few hundred years. A radiocarbon date of 1580 ± 150 years B.P. has been obtained on detrital charcoal from the bedded silt-sand-gravel sequence. The two most recent events of surface faulting have occurred subsequent to deposition of the charcoal. The interval between these two events is probably 500 to 1000 years.

4. Preliminary analysis of the relationship between the main fault and the scarp-derived colluvium suggests that the amount of tectonic displacement during at least some of the past events at this locality was several meters, indicating that earthquakes of magnitude 7, or larger, have occurred along this segment of the fault.

In addition to these conclusions, the following observations were made at the Kaysville site; these observations affect geologic interpretations of amount of tectonic displacement per event and recurrence intervals of surface faulting:

1. Back-tilting of the downthrown block toward the main fault may have increased the vertical stratigraphic separation across the main fault plane by as much as a factor of 2, relative to the true tectonic displacement. This phenomenon should be considered in developing estimates of earthquake magnitudes based upon fault displacement.

2. The most recent surface faulting along this segment of the Wasatch fault produced a series of grabens bounded by en echelon, antithetic faults. This represents a change in the pattern of surface faulting.

3. Detailed study of sequences of scarp-derived colluvium provides a useful technique for evaluating recurrence of surface faulting.

GEOLOGIC INVESTIGATION OF RECURRENCE INTERVALS AND RECENCY OF FAULTING ALONG THE SAN GREGORIO FAULT ZONE, SAN MATEO COUNTY CALIFORNIA

CONTRACT NO. 14-08-0001-16822

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SUMMARY

INVESTIGATIONS

1. Analysis of the Año Nuevo thrust fault to determine the recency of movement, number of episodes of movement, recurrence interval, displacement rates and expected magnitude of earthquake events on this secondary trace within the San Gregorio fault zone.

2. Analysis of the sedimentary deposits and associated fossils on the first marine terrace at Point Año Nuevo to determine the history of the formation of this broad marine terrace.

3. Analysis of the Frijoles fault complex to determine the history of late Pleistocene and Holocene behavior (displacement rates, recurrence interval, recency of movement, etc.). The Frijoles fault complex is one of three primary traces which comprises the San Gregorio fault system and consists of numerous enechelon traces which exhibit both reverse and strike slip displacement. Part of the study is to attempt to determine the relationship of movement along the reverse fault and along the strike slip traces.

RESULTS

1. Detailed mapping of the terrace stratigraphy and the Año Nuevo thrust fault in sea cliff exposures located south of Point Año Nuevo indicates that since the formation of the erosional platform of the first marine terrace (either 80,000 or 105,000 years B.P.) a minimum of four and possibly as many as six faulting events have occurred along this fault. Each of the episodes of faulting, that are recorded in the terrace stratigraphy, is the result of 2½ to 4½ feet of vertical displacement accompanied by surface rupture and the formation of scarps. It is highly probable that more than six faulting events have occurred over this time interval but that some were too small to be preserved in the stratigraphic record. In any event, average recurrence intervals along the Año Nuevo thrust fault are approximately 16,000 years.

2. We have collected fossil material from several locations near the base of the first marine terrace at Point Año Nuevo and have completed detailed stratigraphic sections within the marine terrace deposits. Age dates on the fossil materials may allow us to determine the history of formation of the terrace platform.

3. We have cleaned and logged the wall of an abandoned quarry which exposes the reverse trace of the Frijoles fault complex and a fifteen foot deep exploratory trench placed across the fault trace on the floor of the quarry. Exposed in the walls of the quarry and the trench is a complex zone of faulting consisting of components of both reverse slip and right lateral strike-slip. Also exposed in both the trench and quarry walls are colluvial deposits (below the fault on the footwall block) exhibiting five weakly- to moderately-developed soil profiles. These buried soils suggest a minimum of six faulting events, each of which resulted in 3 to 4½ feet of vertical displacement. As probably less than half of the total marine terrace sequence is exposed in the excavations on the downthrown block, it is reasonable to assume that the record of possibly as many as twelve to fifteen faulting events may be preserved in the terrace sediments. This very roughly suggests an average recurrence interval of between 6,000 - 10,000 years for this fault trace.

   A layer of fine- to medium-grained sand which is the result of emplacement by several liquifaction events is found along the entire length of the fault plane exposed in both quarry wall and trench. These liquifaction events have apparently occurred within the underlying marine sands located near the base of the terrace sediments on downthrown block. To date, we have not been able to determine the number of liquifaction events and it appears as if the liquified sand did not commonly form sand blows at the surface. The relationship of the liquified sands to the recent soils is presently under study.

Soil Morphology and Fault Movement

14-08-0001-G-520

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Investigations

1. Work on this project was initiated on September 15, 1978.

2. Soils that may have been influenced by movement in fault zones were sampled at three sites on the Black Rock Fault in Nevada. It is estimated that time since last movement at these sampling sites varies from 500 years to possibly 20,000 years.

3. Soils were sampled adjacent to the San Andreas Fault at Cutty Valley, California. This site represented movement of approximately 120 years ago.

Results

The samples are now being processed in the laboratory so that interpretations can be made.

Paleomagnetic Studies of Holocene Fault Displacement

8-9930-02158

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Goals

1. To further develop a paleomagnetic technique for dating Holocene sediments based on the secular variation of the geomagnetic field.
2. To apply this technique to a study of the displacement history of faults in southern California showing Holocene offset.

Sufficient work on the Holocene history of secular variation of the geomagnetic field in western United States has now been completed to attempt to use our knowledge of this history in dating Holocene sedimentary deposits. Useful control exists for a period extending back from the present to about 7000 B.P. (radiocarbon years). At present there are significant gaps in this record, but even at this early stage it appears worthwhile to test the application of this concept to the problem of the displacement history of active faults and the recurrence intervals between earthquakes.

Investigations

1) Approximately 75 additional samples of a thin unit of aeolian silt (K. Sieh's unit 71; JGR, v. 83, p. 3907ff) were collected from bulldozer cuts and creek banks at Pallett Creek, 6 km south of Pearblossom, California. These samples were collected in localities as far from the modern trace of the San Andreas fault and as far from previous sample locations as feasible in order to investigate the possibilities that a) right-lateral shear along the San Andreas fault might locally rotate sediments and hence deform their remnant magnetic directions, and b) different sample groups give differing virtual geomagnetic pole (VGP) directions. Preliminary conclusions from previous groups of samples are that a) there is no rotation (greater than 5°) due to right-lateral shear and b) VGP's for this particular unit are similar from one group of samples to another. (The latter statement can not be made for all units sampled at Pallett Creek.) The VGP for samples from this unit agree very closely with the VGP predicted for a unit of its age by the archeomagnetic curves of R. L. Dubois (unpublished data), now that the radiometric age has been revised upward from 1470 yrs B.P. to 1530 yrs B.P. (K. Sieh, personal communication).

2) Laboratory analyses were completed on all samples from Pallett Creek.

TECHNICAL REPORT SUMMARY

Patterns and Rates of Recurrent Movement Along the Wasatch - Hurricane - Sevier Fault Zone, Utah During Late Cenezoic Time

by

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Study of the morphology of the Wasatch fault scarp has been extended to the northern limits of the fault near Tremonton, Utah so the project is nearly completed and a number of preliminary conclusions may be made. Thirty-eight additional profiles across the scarp have been made in the area between American Fork and Tremonton, Utah which provide the basic data for the study. Examples of these are shown in Figure 1. From these and other profiles in Utah County it is possible to recognize remnants of three major erosional surfaces which can be correlated with considerable confidence throughout the entire length of the fault (figure 2). These surfaces and their associated faceted spurs, together with the fault scarps in the sediments of Lake Bonneville provide the framework for interpreting the nature of faulting along the Wasatch front and the history of recurrent displacement.

The fault scarps in the shoreline deposits of Lake Bonneville have been mapped by Woodward and Clyde using low-sun angle photography and are important in that they provide the best insight into the characteristics of normal faulting and the early evolution of the resulting scarps. These scarps occur as a series of discontinuous ridges, some of which are tens of meters high. In most cases the fault scarp rises above the general surface of the lake terraces which would indicate that the eastern block or footwall has been the active block being displaced upward while the western block or hanging wall has remained stationary and inactive. Judging from the height of scarps in the Basin and Range province produced by historic earthquakes, a single event would produce a scarp rarely more than 4-5 meters high. The scarps tens of meters high in the sediments of Lake Bonneville would thus most likely represent several tectonic events.

The lower faceted spurs preserved in the bedrock of the mountain front range from 200 to 600 feet above the highest lake terrace and indicate a series of older recurrent displacements along the entire length of the fault. When the erosional surface at the top of these spurs is traced from north to south it is seen to rise and fall to form a series of culminations and depressions. This is interpreted to be the result of scissor, or ramp, type displacement.

The erosional surface of intermediate height ranges from 600 to 1000 feet above the Bonneville shoreline. As shown in figure 2, this surface also rises and falls along the strike of the fault; but the culminations and depressions are much more subdued than those in the lower level. This probably results from the fact that the intermediate surface is much older and its correlation represents a greater degree of generalization plus the strong likelihood that some culminations and depressions are removed by subsequent movement along the fault in formerly stable regions. In addition to the main intermediate level, several secondary or local intermediate erosional surfaces occur, but these appear to merge with the main surface when traced along strike.

The high erosional surface shown in the solid line in figure 2 ranges from 2000 to 2500 feet above the level of Lake Bonneville. Correlation of this surface along the mountain front is somewhat more subjective because its remnants are much older and smaller than that of the lower surfaces. The existance of a general erosional surface at this line which is interpreted to represent a general period of tectonic stability along the Wasatch front, however, is well documented by the series of profiles (figure 1). In the vicinity of northern Salt Lake County and southern Davis County this surface is several kilometers wide and represents a major long period of tectonic stability in that region while to the north and south the period of stability was relatively short. Remnants of older, higher erosional surfaces are easily identified in many areas but from the data obtained in this study they cannot be correlated with confidenc throughout the length of the fault.

A Conceptual Model of Displacement in Normal Faults

From the data collected in this study it is possible to construct a conceptual model of the nature of displacement along the Wasatch fault and the evolution of the fault resulting from a series of recurrent displacements. The main idea developed is summarized graphically in a series of diagrams drawn in the plane of the fault (figure 3).

A single tectonic event would produce a local scarp up to 4-5 meters high. The scarp would extend for possibly several kilometers and would represent scissor or ramp type displacement. In most cases the upthrown block would be the active block moving up beyond the essentially stationary or passive downthrown block. Antithetic faults producing local grabens, of course, would be an exception. A series of tectonic events would produce a series of scarps like those shown in figure 3a.

Continual recurrent movement would produce larger compound scarps of greater areal extent separated by areas of tectonic stability (figure 3b).

Prolonged recurrent movement causes many of the first and second order scarps to merge and produce a continuous scarp with large culminations in areas of previous displacement and depressions in areas of previous tectonic stability (figure 3c). At this stage stress along essentially the entire fault could be relaxed and tectonic stability would occur long enough to produce significant slope retreat and an incipient pediment at the base of the fault scarp.

Resurgence of tectonic activity would then result as stress built up along the fault zone. Many small and local culminations and depressions resulting from first and second order scissor-type displacement would be removed by displacement in the formerly inactive areas, so that the rising scarp would become a continuous cliff (figure 3d).

Subsequent cycles of recurrent displacement separated by periods of tectonic stability would produce a series of erosional surfaces preserved at the top of compound faceted spurs.

History of Displacement along the Wasatch Fault

1. An early cycle of tectonism produced a series of culminations and depressions forming discontinuous mountain ranges along what is now the Wasatch front (figure 4a). Ranges occurred from (a) Tremonton to Brigham City, (b) Brigham City to Bountiful, and (c) Salt Lake to Nephi. Minor periods of stability during this major period of tectonism occurred locally within each separate range.

2. A general period of tectonic stability occurred along the entire Wasatch front and persisted long enough to develop the high level erosional surface shown in figure 2. The period of stability was longest in the Bountiful-northern Salt Lake City region where remnants of the erosional surface are several kilometers wide.

3. A second cycle of tectonism occurred and developed a continuous scarp along the entire Wasatch front with depressions in the vicinity of Brigham City and Bountiful (figure 4b).

4. Tectonic stability followed permitting slope retreat along the scarp and an erosional surface at the base of the mountain front.

5. Recurrent tectonism followed developing a fresh scarp along the entire mountain range and elevating the two previously formed erosional surfaces (levels now referred to as the high and intermediate surfaces) (figure 4d).

6. Tectonic stability followed with associated slope retreat forming the low level surface (figure 2).

7. Resurgent tectonism along the entire fault zone developing a fresh scarp at the base of the mountain front which is now eroded into the faceted spurs 200-400 feet above the level of Lake Bonneville.

   The widespread occurrence of fault scarps along the Wasatch front in Lake Bonneville sediments together with the freshness of the most recent faceted spurs suggests that we are still in the later stages of the last period of active tectonism, which can be expected to continue intermittentl for some time to come.

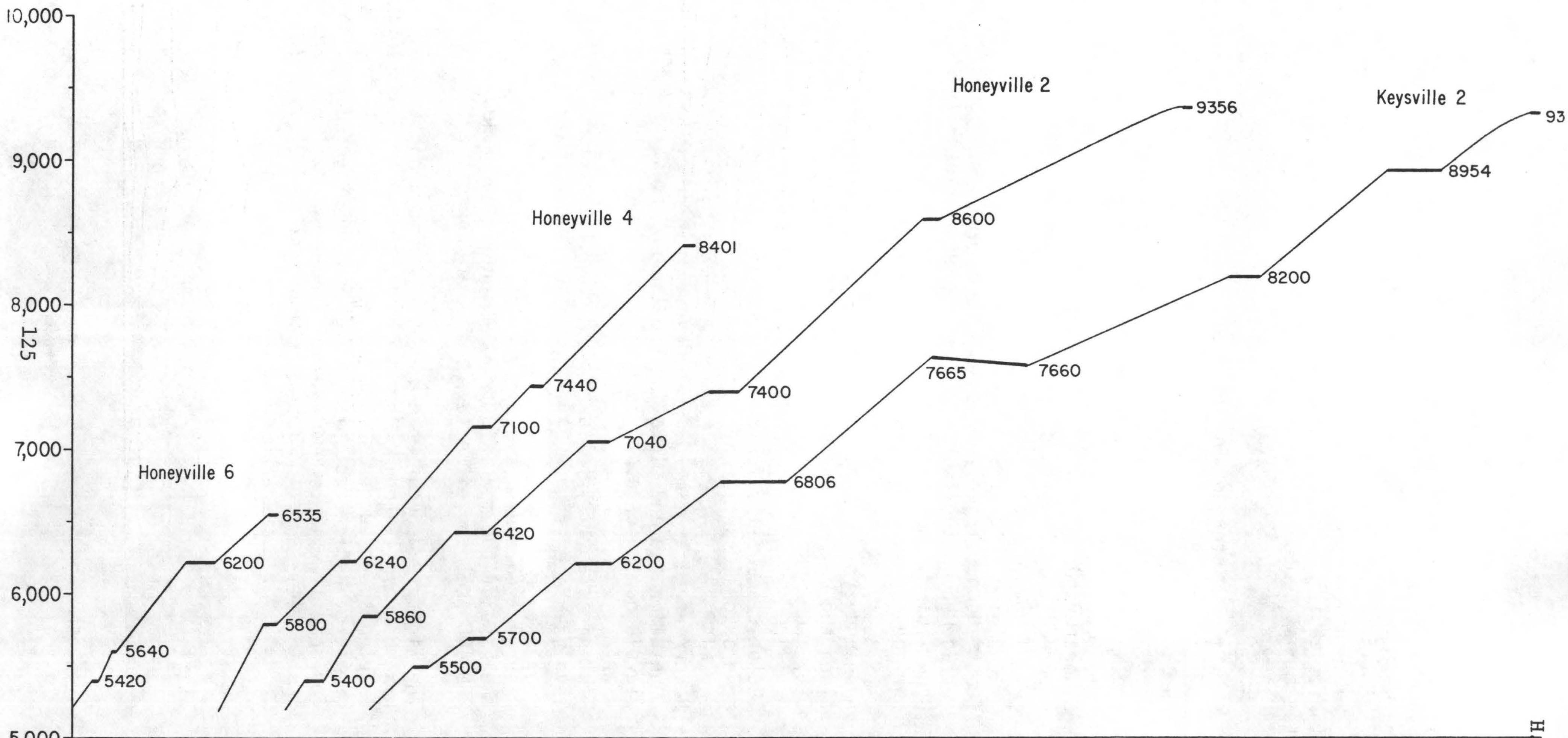
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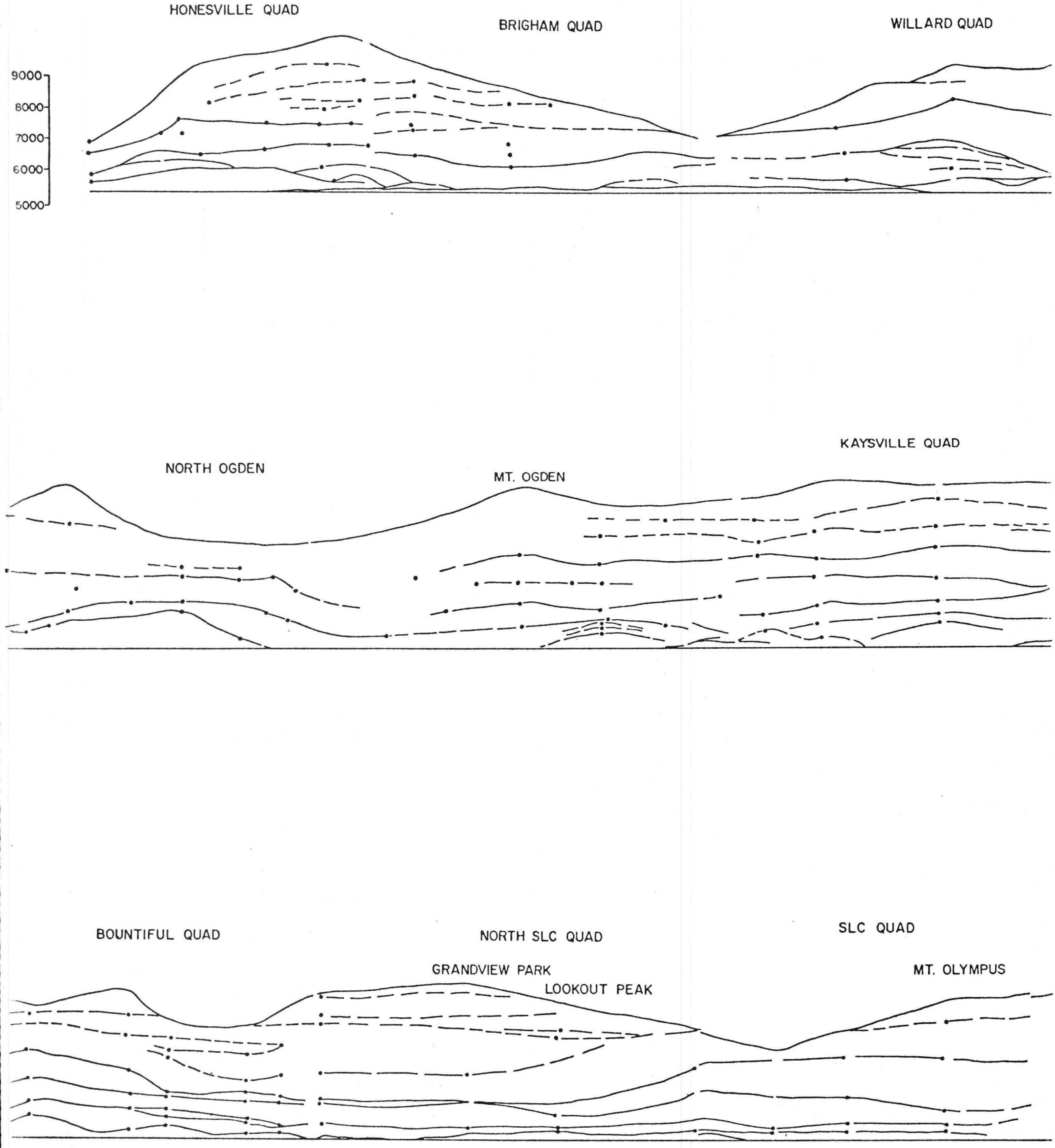
Figure 1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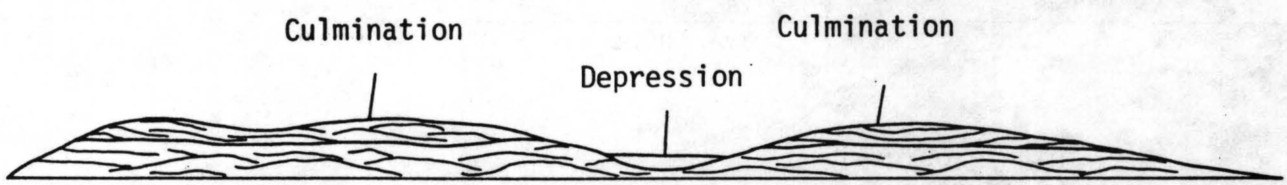
BOUNTIFUL QUAD
NORTH SLC QUAD
SLC QUAD
GRANDVIEW PARK
LOOKOUT PEAK
MT. OLYMPUS

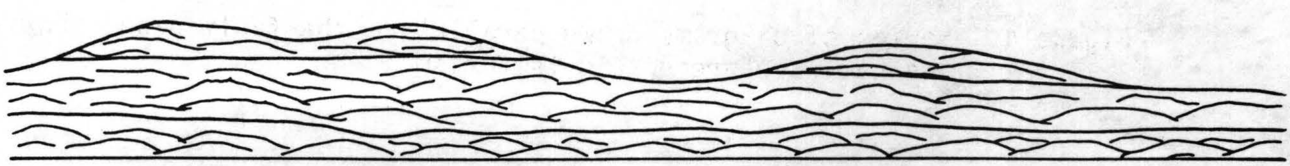
Figure 2

a. Discontinuous scarps produced by several tectonic events.

b. Larger compound scarps produced by prolonged tectonism.



c. Continuous scarp produced by recurrent tectonism. Culminations and depressions occur in areas of previous tectonic stability.



d. Mature scarp showing culminations and impressions.

Figure 3. Conceptual model showing the evolution of the normal faults.

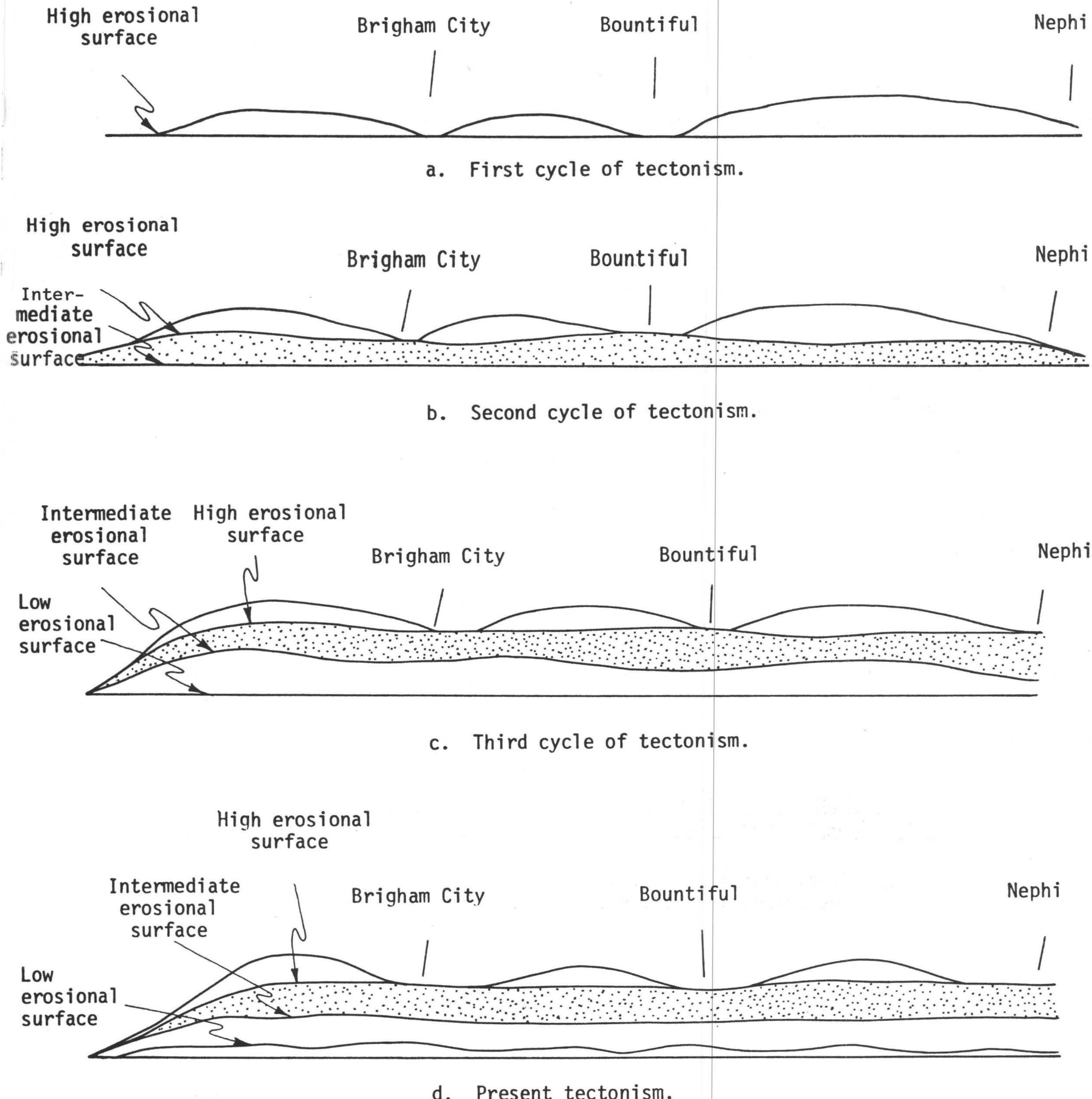


Figure 4. Series of diagrams drawn parallel to the fault plane showing the cycles of recurrent tectonism.

Correlation and Dating Quaternary Sediments by Amino Acids

9-9460-01996

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Investigations

1. Established a program with eleven laboratories for inter-comparison of amino acid racemization data from fossil shells.

2. Measured the extent of racemization of amino acids in regions of a single mollusk valve to determine intrasample variability.

3. Measured the extent of racemization in Saxidomus giganteus from outcrop near Fort Funston on the Pacific Coast south of San Francisco.

4. Estimated the ages of cetacean ear bone nuclei of manganese nodules and calculated the rate of accretion of ferromanganese oxides by measuring the extent of racemization of isoleucine and aspartic acid.

5. Determined the extent of racemization in seven samples from a pre-Neandertal site at the Cave of l'Arago, near Tautaval, France.

6. Established a new laboratory for amino acid biogeochemistry at 3475 Deer Creek Road, in Palo Alto, CA.

Results

1. During the last ten years there has been an ever increasing interest in the measurement of the extent of racemization of amino acids in geological samples. This interest has been partially sustained by the potential this measurement has for determining the geochronology and paleothermometry of Quaternary sediments. Results from several laboratories now appear in the scientific literature. How closely analytical results from these different laboratories compare has not been determined. To establish a basis for interlaboratory comparison we homogenized the pulverized valves of Saxidomus giganteus, a pelecypod collected from U.S.G.S. Cenozoic Locality 1497 at Willapa Bay, Washington, and we distributed samples to the following participating laboratories. Carnegie Institution of Washington, Lamont-Doherty Geological Observatory, NASA-Ames Research Center, Scripps Institution of Oceanography, University of Alberta in Canada, University of Arizona, University of Colorado, University of Delaware, University of Texas, and Utah State University. Results from this comparison will be summarized in the next semi-annual technical report.

2. In our previous report we summarized results of our comprehensive study on the correlation and chronology of estuarine deposits at Willapa Bay, Washington, based on amino acids in Saxidomus giganteus and Ostrea lurida. This work was based largely on amino acids in the hinge of these pelecypods. In other localities where this methodology may be useful, only random shell fragments may be

present. It was of interest, therefore, to determine the variability of racemization measurements in different parts of a shell. A single valve of Saxidomus was cut into five regions (hinge, two aductor muscle regions, growth edge, and center). The degree of racemization of the amino acids in these regions varied within the expected range for the technique. Thus random fragments of Saxidomus can be used for correlation and chronology.

3. The amino acid dating technique has been applied to Saxidomus in a single outcrop on the beach near Fort Funston south of San Francisco. This outcrop lies stratigraphically below an ash bed for which radiometric dating shows an age of 1,100,000 years. The amino acids in these shells are racemic, i.e., at equilibrium. The amino acid results are in agreement with the radiometric evidence, and indicated that the shells are older than about 700,000 years. Because the amino acids are at equilibrium only a minimum age estimate can be given.

4. Amino acid dating methods have been applied to the cetacean ear bones from nuclei of eight manganese nodules from the North Pacific Ocean. From the extent of racemization of isoleucine and aspartic acids the ages were estimated to range from about 0.4 to 6 million years, and the rates of accumulation of ferromanganese oxides were estimated to be slow, less than 10 mm/m.y. The growth rates compare very favorably with rates obtained by other methods (K-Ar, fission track, ^{230}Th, ^{231}Pa, ^{10}Be, and ^{26}Al). Our results contribute to a resolution of the controversy concerning whether or not rates of growth of manganese nodules in the deep sea are very rapid or very slow. Our results support the latter premise.

5. Near the village of Tautavel, France, a cave has yielded fossil hominid remains of pre-Neandertal aspect. This site represents an important datum point in the history of hominids in Europe. We have measured the extent of racemization of amino acids in seven bone samples from this site. D/L ratios of aspartic acid range from about 0.53 to 0.59 which correspond well with results obtained earlier by Scripps Institution of Oceanography. Interpretation of ages is difficult because of the lack of a calibration site or a temperature history. The ages of the samples are probably at least 60,000 years but may be as old as 300,000 years.

6. A new laboratory for amino acid biogeochemistry has been established as part of the marine organic geochemistry program within the Western Geologic Division of the Survey. This laboratory will initially concentrate on research and on applications of amino acids to geochronology and paleontology. The laboratory is now fully operational.

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PRELIMINARY STUDY OF POSSIBLE EARTHQUAKE DEFORMED SEDIMENTS IN KERN LAKE, KERN COUNTY, CALIFORNIA

July 1978

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SUMMARY

Nine excavations have been made on the margins of Kern Lake, Kern County, California. The stratigraphic section revealed in the test pits consists of interbedded sands, silts and clays. Sand and silt layers apparently pinch out basinward, suggesting at test pit No. 2 a southerly sediment source. Two local unconformities, 40 to 48 cm apart stratigraphically, truncate complex load and intrusion structures (Fig. 1) which we believe are the result of strong seismic shaking. Load structures represent the sagging, sinking, or partial collapse, with or without liquefaction, of coarser-grained sands into finer-grained silts or clays. Intrusion structures are the result of forceable injection of liquefied sand into overlying or underlying strata. Composite structures, probably the result of injection of liquefied sand with subsequent collapse, are also exhibited in the test pits.

A close relationship between the load and intrusive structures and the unconformities which truncate two distinct groups of deformation structures indicates two abrupt events separated by a period of quiescence. The time between these events can be estimated from a 1.3 mm/year rate of deposition from Croft's (1968) data and the 40-48 cm thickness of lake sediments between the unconformities. On this basis, a 300 to 370 year interval between deformation events is estimated. An origin by artesian spring flow or escaping gas would seem unlikely to cause such distinct and infrequent deformation events.

In view of the known major historic and pre-historic earthquakes which have occurred on the San Andreas fault (Sieh, 1977) 30 km to the south, an

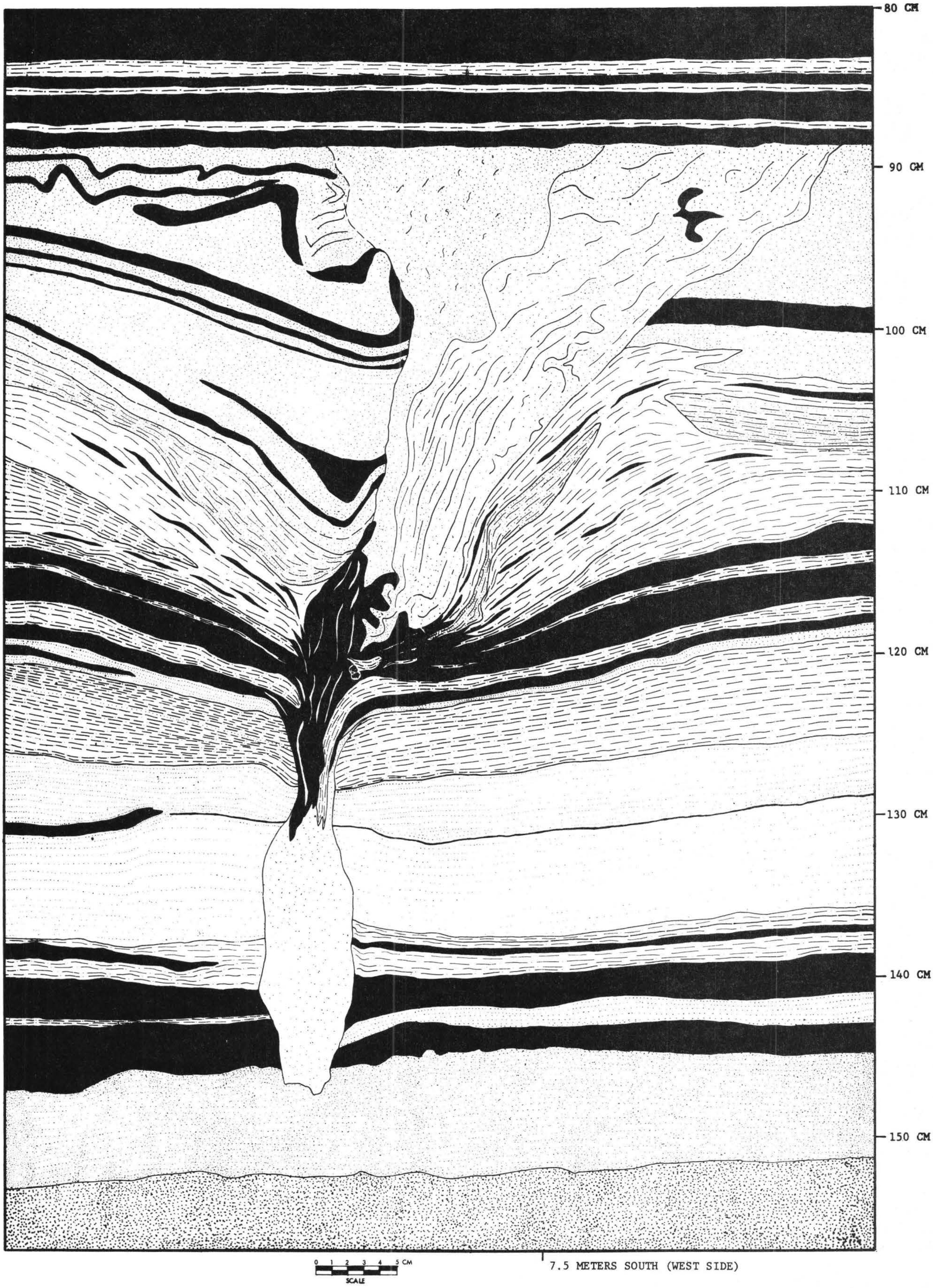

Fig. 1 - Detail of sediment intrusion (see Fig. 4 for location).

origin by earthquake induced liquefaction and deformation is probable. The similarity of the 255 $\pm^{30}_{20}$ average recurrence interval estimated for major events on the San Andreas fault at Wallace Creek 60 km to the west (Sieh, 1977) and our estimated 300-370 year interval between events supports the earthquake shaking hypothesis.

Although it is somewhat premature to extend conclusions based on work in progress, the results of this project to date suggest the following specific observations:

1. Marginal sediments of Kern Lake exhibit a variety of load structures and intrusive structures consistent with the hypothesis that they originated during earthquake shaking.

2. The complex internal relations shown in the structures suggest a sequence of events including injection into overlying or underlying strata by liquefied sand, with subsequent collapse.

3. Preliminary results show at least two distinct deformation episodes separated in time by approximately 350 years.

4. Carbonized wood fragments and shell material within the Kern Lake sedimentary succession can be dated by ^{14}C, and possibly by amino acid epimerization measurements. Samples for preliminary ^{14}C dates have been submitted.

5. Deformation structures are commonest where sands and clays are intercalated, with a preponderance of sand over clay.

Verification of earthquakes reported by Sieh (1977) and Jahns (1977), as well as important information on the "felt-area" of these earthquakes, can be obtained by continued investigation of lacustrine sediments. It is significant that the Kern Lake basin is near the San Andreas, the Garlock and the White Wolf faults, all of which have shown historic movement. Information on timing of seismic events in this area will extend our knowledge of earthquake recurrence intervals in south-central California, and the research may provide a general method of estimating recurrence intervals in any area where lacustrine deposits occur.

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Soil Correlation and Dating, Western Region
8-9540-02192

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Investigations

1. To study change of properties in well documented time sequences (chronosequences) of soils, fifty soil profiles (3 to 7 samples each) have been described, sampled, and submitted for laboratory analysis. Partial laboratory data has been completed on 24 of these profiles. Profiles sampled include soils formed on arkosic alluvium of the Merced River and volcanic alluvium along Dry Creek in the northeastern San Joaquin Valley, California; soils formed on metamorphic and volcanic colluvium in the Oroville, Auburn, and Sonora areas of the Sierra Nevada foothills; soils formed on volcanic alluvium along the Cowlitz River west of the Washington Cascades; and soils on Neoglacial moraines derived from granitic rocks in the Front Range of Colorado. We also have access to data for chronosequences of soils in New Mexico (arkosic and mixed sources) and central Pennsylvania (mixed sedimentary sources). The areas listed above encompass a wide range of climates and vegetation.

2. New field work will concentrate on chronosequences of soils in the Mojave and Great Basin deserts, Southern California, along the California and Oregon Coast, and in other areas where well studied and dated sequences of Quaternary deposits occur.

3. Replicate Merced River, Dry Creek, and Cowlitz samples have been submitted to J. N. Rosholt for uranium-trend dating. Results from the Merced River samples indicate remarkably close correspondence between previously assessed soil age and uranium-trend age.

4. A terminal-operated program, MINITAB, is being used for storage, plotting, and statistical interpretation of soil data.

Results

1. Morphological properties observable in the field are usually the most reliable index of soil age. We have found the following properties to be most useful: 1) presence, nature, and thickness of B horizons, 2) depth to unweathered parent material, 3) B horizon structure, 4) location, thickness, and abundance of oriented clay films in B horizons, 5) B horizon texture and consistency relative to A and fresh C horizons, 6) nature, abundance, and size of interstitial and tubular pores in B horizons, and 7) color of B horizon relative to A and C horizons. In old desert soils where B

horizons have been eroded, the character of subsoil horizons of calcium carbonate accumulation become more diagnostic of soil age than the overlying B horizons.

2. Thin sections of soil B horizons reveal progressive textural development. Stages of development can be recognized for correlation purposes. We will section some A horizons to study and perhaps quantify etching, alteration, and depletion of weatherable minerals.

3. Particle size analyses provide valuable information for correlation and dating. Content of less-than-2 and less-than-1 micron clay constitute two of the most reliable age indices for soils. Silt and sand fraction data permit categorization of parent materials and adjustment of clay contents for profile stratification or textural differences between profiles.

4. Bulk density analyses show very small standard deviations between replicate samples. Bulk density increases rapidly during the first 10,000 to 20,000 years of soil development, then increases at a slower but steady rate to a limiting value of about 2.0 g/cc. The product of bulk density and clay content, summed through a soil profile above fresh parent material correlates very well with soil age.

5. Semiquantitative clay mineralogy appears to be a promising technique, although our present data are very limited. Arkosic chronosequences tend to show progressive depletion of illite and concomitant increase in kaolinite/halloysite, whereas volcanic parent materials show a gradual buildup in smectite with time.

6. Soil properties related to leaching (pH, extractable cations, base saturation) become more useful as age indices in regions where precipitation is moderate to high. pH decreases and total profile hydrogen ion content increases systematically with age in the Merced chronosequence. In the foothills, however, older soils are invariably buried beneath younger deposits and the pH and extractable cations change rapidly following burial.

7. Cation exchange capacity increases with clay content and therefore with the age of a soil. Because CEC is also affected by organic matter and clay mineral composition of the soil, it tends to be less useful as an age index than other soil properties. Determination of CEC and extractable cations, however, permit calculation of base saturation percentage, which may be a useful parameter for soils in humid regions.

8. Well drained and oxidized soil profiles display increases in free iron oxides with time. Free iron appears to be lost in soils subject to reduction during their development. Total profile free iron oxides and B/A or B/C ratios are generally the most useful parameters for age regressions.

9. Organic carbon values, like bulk density determinations, are readily reproducible. Organic carbon shows a smooth exponential decrease with

depth, but the rate of decrease is greater in older soils. It may be possible to determine approximate soil age back to about 100,000 years, independent of parent material, from organic carbon profiles. Carbon is also a valuable aid in recognition of buried soils.

10. In general, profile summations (e.g., total clay in profiles) and horizon ratios (e.g., free iron in B/free iron in A) tend to correlate better with time than do absolute values of individual variables.

11. Under ideal circumstances (a soil adhering closely to a well studied chronosequence), a careful profile description and full laboratory analysis will permit accurate age estimation of relict soils within about 25% of the stated value. Further work will attempt to reduce this margin of uncertainty.

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Quaternary Dating Techniques

8-9530-01559

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Investigations

1. Completed field studies of weathering rinds, geomorphic sequences, and exploration for datable materials in the lowlands between Mt. Rainier and Gray's Harbor, Washington.

2. Completed field studies of weathering rinds, morphologic parameters, and soil development on the glacial chronosequence near McCall, Idaho.

3. Completed mapping of surficial deposits and Quaternary basalts of the lower Raft River Valley, Idaho.

4. Mapped alluvial fans and measured caliche rinds on faulted fan gravels near Arco, Idaho.

5. Continued study (with Maynard Fosberg, J. D. Love, and W. E. Scott) of surface and buried soils in the loess sequence immediately overlying lava flows and glacial deposits in and near the eastern Snake River Plain, Idaho.

6. Collected (with Irving Friedman) obsidian pebbles from 1.5 m deep pits in Lake Bonneville strandline deposits for obsidian hydration dating studies. Studied strandline sequences and associated deposits containing obsidian in three different areas from three different sources in the Fillmore to Milford, Utah, areas.

7. Collected data on morphological and erosional parameters of the sequence of terraces along the Rappahannock River, Virginia. These data will be used to analyze landform modification and scarp degradation with time.

8. Completed sample and data collection from a weathering chronosequence on lava flows from the southwest rift of Mauna, Loa, Hawaii.

9. Described and sampled a soil chronosequence formed in middle to late Quaternary deposits in north-central Colorado in order to determine changes in key soil properties.

10. Gathered information for internal reports on 1) a summary of experimental Quaternary dating techniques, and 2) the potential of 50 Quaternary sequences in the United States for experimental dating studies.

Results

1. Additional work on the sequences of deposits for which weathering rinds were measured near Gray's Harbor and Mt. Rainier, Washington, has shown that Salmon Springs deposits near Gray's Harbor is probably older than the last series of high-sea stands (75-125 ka ago) and that Hayden Creek till near Mt. Rainier along the Cowlitz River Valley apparently is all of one age. Wood was collected above Salmon Springs deposits for enrichment ^{14}C dating and pumice was collected from within Hayden Creek deposits for fission track and K-Ar dating. These dates should provide calibration for the relationship between weathering-rind thickness and time, as well as date these previously undated deposits.

2. Data collected for the chronosequence of glacial deposits near McCall, Idaho, demonstrate that soil development and weathering-rind thickness are excellent systematic indicators of relative age. These data also provide constraints on correlations and on numerical ages. In contrast, various parameters related either to surface weathering or granitic stones or moraine morphology proved less systematic indicators of age.

3. Study with Maynard Fosberg (University Idaho, J. D. Love, and W. E. Scott) of surface and buried soils in loess in and near the eastern Snake River Plain demonstrate a systematic relation with time. For example, several backhoe pits through the loess mantle on a basalt dated by G. B. Dalrymple as 78±15 ka (thousand years) old show a typical postglacial soil in 2 meters of loess with no buried soil near the basalt-loess contact. But on deposits dated as 145 ka old by combined obsidian hydration and K-Ar studies, loess with a typical postglacial soil rests on a buried soil with a textural B horizon developed in an older loess unit. Samples are being processed for more K-Ar dating and soils analysis of other loess mantled basalts, gravels, and glacial deposits, many of which are locally faulted, to provide additional information on the loess-soil record above dated basalts, and thereby to determine deformation rates in this tectonically active area.

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Tephrochronology of the Western Region

8-9540-01947

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Summary

Continued sampling, chemical and petrographic analysis, and fission-track age dating of tephra (ashes and tuffs) of young geologic age in order to provide age control for studies of recent tectonism in California, Nevada, Oregon, and Washington. Neutron activation, X-ray fluorescence, and electron microprobe analyses of separated volcanic glass and crystals are used to identify widespread tephra units of known radiometric age. New tephra units identified by chemical and petrographic analysis are dated by appropriate radiometric age dating methods.

Investigations

1. Continued analyses of a suite of well-dated (^{14}C) samples of late Quaternary Tephra collected from Mt. St. Helens (in cooperation with D. Mullineaux, Branch of Engineering Geology, Denver) to test resolution of chemical fingerprinting technique on tephra erupted within a short time interval (about 40,000 years) and to provide chemical and age reference standards for down-wind tephra sampled in eastern Washington, Oregon, and Nevada (see Results, item 1).

2. Continued analysis of Quaternary Tephra collected from central Washington (in cooperation with R. Waitt, Branch of Western Environmental Geology), to determine age of Quaternary deposits and geologic events by correlation with reference section at Mt. St. Helens and other Cascade Range sources (see Results, item 2),

3. Continued sampling and analyses of Quaternary ashes and tuffs from Lake Lahontan basin of northwestern Nevada (in cooperation with Jonathan Davis, Nevada Archeological Survey), to correlate with Cascadian sources of late Quaternary age.

4. Collected oriented pumice cobbles and fine ash samples from the Rockland Pumice ash-flow tuff southwest of Lassen to determine its paleomagnetic direction (in cooperation with J. Hillhourse, Branch of Petrophysics and Remote Sensing). This tuff is the near-source correlative of the widespread Maidu ash of northern and central California. The study is intended to confirm the age of this ash, presently estimated at 0.6±0.1 m.y.

5. Obtained and began analyses of a suite of tephra from the Humboldt County area (in cooperation with K. R. Lajoie and S. Morrison, Branch of Ground Motion and Faulting). The age and correlation of these ashes has an important bearing on the siting of the Humboldt Bay nuclear reactor plant.

6. Collected and began analyses of a suite of samples from the Bishop ash in the type area near Bishop, California, to determine if small systematic or random chemical and petrographic variations can be detected within a vertical section of this thick ash-fall tephra unit. This study is important in establishing long-distance correlations with down-wind exposures of the Bishop ash.

7. Continued analyses of tephra collected from Quaternary basins of the Mojave desert and the Lake Tecopa area of southeastern California (see Results, item 3).

8. Continued analyses of early and middle Pleistocene tephra in the Ventura basin of southern California (in cooperation with R. Yerkes, Branch of Western Environmental Geology, and K. R. Lajoie, Branch of Ground Motion and Faulting).

9. Obtained and analysed samples of several widespread tephra units in the central region of the U.S. (in cooperation with G. Izett, Tephrochronology of the Central Region Project). An exchange of samples was intended to cross-check and calibrate identification methods used by the two tephrochronology projects, and to identify and correlate widespread late Cenozoic Tephra in the coterminous U.S. (see Results, item 3).

Results

1. Seven of thirty ashes sampled at Mt. St. Helens have been analysed by neutron activation anaylses of the separated volcanic glass. All but two of these ashes, Ye and Yn, can be distinguished on the basis of the chemical composition of the glass. Ashes Ye and Yn are superposed and were probably erupted within a very short time of each other. They cannot be distinguished within the precision of the analyses at the present time.

2. Two ashes, Sg and So, correlate well with two thin ashes, 581B and 581A, found in scabland flood deposits of central Washington. These data support earlier correlations made on the basis of petrographic data by D. Mullineaux, and date the scabland floods at about 13,000 ^{14}C years b.p., the approximate age of unit S at Mt. St. Helens.

3. Preliminary analyses of samples provided by the Central Region Tephrochronology Project indicate the presence of Pearlette type B ash in the Manix basin of central mojave desert, California. Table 1 shows analysis of the ash from Manix basin, compared with type "B" Pearlette ash from the Borcher's locality in Kansas. The match in chemical composition of the glass in the two samples is very good (similarity coefficient of 0.97). The data represent a correlation over a distance of about 1500 km. Analyses of type "O" and "S" Pearlette ashes are shown for comparison in Table 1.

Table 1. Partial analysis of Pearlette-type ashes. Iron in percent, other elements in parts per million. Harry Bowman, analyst.

	Mn	Fe	Zn	Rb	Cs	Sm	Eu	Tb	Hf	Ta
1.	270	1.05	90	235	4.0	12.0	0.41	2.05	8.6	4.03
2.	242	1.01	69	266	4.6	11.1	0.41	1.90	7.2	3.80
3.	281	1.20	103	211	3.5	13.3	0.71	2.13	9.1	3.56
4.	287	1.21	106	201	3.7	13.8	0.69	2.20	9.5	3.53
5.	3	0.02	3	9	0.1	0.02	0.01	0.06	0.1	0.02

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1. Type "O" Pearlette ash (~0.6 m.y.), 2. Type "S" Pearlette ash (~1.2 m.y.), 3. Type "B" Pearlette ash (~2.0 m.y.), Borchers loc., Kansas, 4. Ash in Manix basin, Calif., 5. Average analytical error.

Table 2. Partial analysis of the Bishop ash at the Onion Creek locality, Utah. Harry Bowman, analyst. Iron in percent; other elements in ppm.

	Sc	Mn	Fe	Rb	Cs	Sm	Eu	Tb	Hf	Ta
1.	3.17	281	0.55	200	6.1	3.89	0.04	0.60	3.92	2.18
2.	3.16	279	0.51	202	6.2	3.70	0.03	0.65	3.74	2.27
3.	3.20	272	0.50	195	6.1	3.74	0.03	0.61	3.84	2.25
4.	0.03	3	0.02	9	0.2	0.02	0.01	0.03	0.08	0.01

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1. Bishop ash, Bishop, Calif., 2. Ash at Onion Creek, Utah, 3. Ash in Borrego Fm., E. Salton trough, Calif., 4. Average analytical error.

4. Correlation of an ash by G. Izett at Onion Creek, Utah, with the Bishop ash of California on the basis of petrographic characteristics is supported by neutron activation analysis of the two samples (table 2). These ashes also correlate very well on the basis of their glass chemistry with an ash in the Borrego Formation east of the Salton Sea, in southern California.

Earthquake-Induced Structures in Sediments

8-9950-01294

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Investigations

1. Laboratory studies and analyses of cores and sediments collected in the Imperial Valley, Calif.

2. Field investigations and core collection of sediments from ancient Lakes Lahonton (Nevada) and Bonneville (Utah) and modern Utah Lake (Utah).

3. Continuation of studies on the production of deformational structures in sediments by simulated earthquake shaking.

4. Field studies on southern San Andreas sag ponds.

Results

1. Preliminary results from the analysis of cores from the Imperial Valley and their radiographs show that numerous deformation and primary depositional structures exist in the cores. Many of the deformational structures are similar to those seen in outcrops near some of the core sites and to experimentally deformational structures reported in the literature. About two-thirds of the cores have been split, described, and radiographed. The remaining one-third will be completed before January 1, 1979.

2. Outcrops of Lakes Lahonton and Bonneville sediments contain deformational structures. Most, if not all, of the exposures contain sequences deposited in deltas that enter these ancient pluvial lakes. Processes associated with sediment transport, erosion and deposition in deltaic environments, produce a rich and complex record of soft sediment deformation. Deltaic depositional environments are commonly easily identified. However, the depositional environment of these sediments precludes using data from them to determine earthquake recurrence.

Cores were taken from Lake Utah, an existing lake and freshwater remnant of ancient Lake Bonneville. Three 4-m-long and three 2-m-long cores were taken. Radiographic examination of these cores reveals pervasive biaturbation of the sediments that obscures all other primary depositional or penecontemporaneous deformational structures.

Of considerable interest, however, is the occurrence of a volcanic ash bed near the bottom ot the 4-m-long cores. This ash bed may be one of the Mount Mazama ashes (≈6,700 Years B.P.).

3. Equipment for the experimental production of deformational structures by simulated earthquakes is being assembled or ordered. The sedimentation tank has been built and monitoring devices assembled.

4. At least 25 sag ponds are located along a 7-km-long stretch of the San Andreas fault zone in the Mustang Ridge area, Monterey County, Calif. Detailed geologic mapping (scale 1:12,000) of the fault zone in the area shows that the presence of sag ponds is structurally controlled by 1) the most recent break (and main trace) of the San Andreas fault and 2) left-stepping en echelon faults that have at least 10 m of down-to-the-west surficial expression.

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Tectonic Analysis of Active Faults

8-9900-01270

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Investigations

1. Examined and measured profiles of the scarps produced during the Hebgen Lake, Montana, earthquake of 1959, and other young scarps along the Madison Range, Montana. Reoccupied 1959 photo sites of Witkind and Stacey to record amount of degradation in 19 years. This study is intended to obtain data to understand degradation rates and styles in a climate different from Nevada and California.

2. Visited localities along faults in Senshi Province, People's Republic of China, where 1556 earthquake occurred.

Results

1. Free faces are still abundant on the fault scarps produced during the Hebgen Lake earthquake of 1959, some open fault cracks a meter wide and a meter deep are remarkably fresh. But in comparison to young scarps in Nevada, debris slopes have developed much more rapidly and free faces may disappear completely within a century or less, whereas in Nevada, free faces are estimated to last from 400 to 2000 years at some points along a given scarp.

As a result of the more humid climate in Montana and source rocks that produce a large clay fraction in the colluvium and alluvium, the 1959 fault scarps have reached quasi-stable slope angles of between 40° and 43°. The mechanics of plasticity and viscosity probably are major controls of these slope angles, whereas in the desert climate of Nevada, stable slope angles of between 33° and 37° represent angles of repose of particulate fractions ranging from sand to boulder sizes.

The Madison scarp, approximately 90 km long, on the west flank of the Madison Range, is a composite of scarps of several ages, as indicated by a range of degrees of degradation along strike. Individual profiles also suggest multiple displacements along the same segment of the fault. Although the scarp may be more than 30 m high at a given place, parts of the scarp only a meter or two high have slopes as steep as 40°, whereas the rest may range between 30° and 35°. The last significant displacement before 1959 must have occurred not long before recorded history, because the scarp slope still is only quasi-stable; local small slumps and readjustments occur repeatedly. I would not be surprised to learn that the next previous displacement of 1 meter or more occurred no more than a few hundred years ago.

2. Chinese geologists have interpreted a graben-like structure in which the Wei and Yellow Rivers flow and join near the site of the great 1556 earthquake in Senshi Province. South of the Wei River prominent north-facing range fronts are clearly fault generated, as indicated by geomorphic features such as faceted spurs. The epicenter of the 1556 earthquake has been placed along this set of range front faults by Chinese seismologists, suggesting that normal faulting may have been the dominant style of deformation causing the 1556 earthquake.

Reports

Wallace, R. E., 1978, Patterns of faulting and seismic gaps in the Great Basin province, in Proceedings of conference VI, Methodology for identifying seismic gaps and soon-to-break gaps: U.S. Geological Survey Open-File Report 78-943, p.

Wallace, R. E. (as member of working group; K. V. Steinbrugge, chairman), 1978, Earthquake Hazards Reduction: Issues for an Implementation Plan: Office of Science and Technology Policy, Executive Office of the President, 231 p.

Revision and Studies of Modified Mercalli Intensity Scale

8-9950-02145

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Investigations

1. Work continues on review of the entire U.S. earthquake catalogue for larger events (I_0>V) and revision and (or) prepreparation of isoseismal maps. Work on this project has been coordinated with and supported a project in the Branch of Global Seismology aimed at the preparation of seismicity maps for all 50 States.

Results

1. Isoseismal maps for over 100 earthquakes throughout the United States have been prepared.

2. Forty-five isoseismal maps in the Mississippi Valley, together with analysis of relationships between the areas shaken at various intensity levels and earthquake magnitude, are being prepared for the open files.

Regional and National Seismic Hazard and Risk Assessment

8-9950-01207

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Investigations

1. The effects of parameter uncertainty on mapped values of acceleration in rock, as presented in the probabilistic 50-year exposure time, 90-percent extreme probability acceleration map for the contiguous United States, continue to be examined. A new computer program for hazard estimation, developed by R. K. McGuire, is being used to evaluate the significance of parameter uncertainty in maximum magnitude, fault-rupture length and attenuation.

2. Additional seismic source zone modeling has been done in the Puget Sound and southeast Missouri areas.

3. Investigation of the nature of earthquake losses by class of construction continues.

Results

1. Levels of ground shaking in the Puget Sound area have been investigated for various distributions of earthquakes at depths ranging between the two extreme cases of all-damaging earthquakes that occur at depths of 50-70 km to all-damaging earthquakes that occur at shallower depths. Accelerations with a 0.10 probability of being exceeded in 50 years range from about 0.10g to 0.50g for the two extreme hypotheses. If 25 percent of the earthquakes are considered shallow (75 percent at depths of about 60 km). The maximum acceleration in rock (in 50 years with 0.10 probability of exceedance) is 0.32g. A hazard map of the Puget Sound area has been prepared showing the 25 percent shallow and 75 percent deep distribution of earthquakes. Inclusion of attenuation uncertainty in the hazard calculation increases the maximum acceleration about 40 percent.

2. Inclusion of uncertainties in attenuation, fault-rupture length, and maximum magnitude in probabilistic hazard calculations in Missouri may increase the accelerations with 0.10 probability of being exceeded in 50 years as much as 2.5 times.

3. A paper has been prepared for presentation at the 2nd International Conference on Microzonation for Safer Construction and for inclusion in the Proceedings of the Conference.

Reports

Algermissen, S. T., and Steinbrugge, K. V., 1978, Earthquake losses to buildings in the San Francisco Bay area: 2nd International Conference on Microzonation for Safer Construction, San Francisco, Nov. 27-Dec. 1, 1978, Proceedings, 12 p. (in press).

Physical Constraints on Source of Ground Motion

8-9940-01915

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Investigations

Stochastic modeling of seismicity statistics (b value) and high-frequency ground motion.

Results

Unlike deterministic modeling, which must be done in the space-time domain, stochastic modeling of a rough fault surface may be done in either the space-time or the Fourier-transform domain. If the slip and stress functions are transformed over the two space dimensions on the fault as well as over time, some important conceptual simplifications result. While the stress function on the fault is a convolution of the slip function with second derivatives of the point-force Green's function in the space-time domain, stress is the product of slip and an impedance function in the transform domain. Energy stored or radiated into the elastic medium is calculable from either the slip or stress transforms via the impedance function. The spectrum of radiated ground motion is directly related to the transform of slip or stress on the fault.

Slip and stress changes in an earthquake are assumed to consist of a smooth coherent part and an incoherent part that is more important at shorter wavelengths. In the broad band of wavelengths between the rupture length and the grain size of the medium, it is assumed that the incoherent component has no characteristic length or time scale. Its spectrum is given by a power law.

It is assumed that the coherent component of stress change (negative in the center of a slip patch and positive around the border) has, on the average, a negative correlation with the initial stress function. The difference between stress and sliding friction tends to become smoother at the length scale of the rupture but rougher at smaller length scales. A large earthquake establishes irregularities that determine the size of future smaller earthquakes. All earthquakes smaller than the depth of the brittle region are aftershocks.

In agreement with Hanks, the fault stress spectrum that is consistent with earthquake stress drops being independent of size is also consistent with an omega-squared far-field displacement spectrum. The slope of the number-moment distribution of earthquakes

$$\log N = a' - b' \log Mo$$

is restricted to the range

$$2/3 < b' < 1$$

with the lower end of the range being favored. The static slip spectrum goes as one over wavenumber squared, which is the same roughness spectrum proposed by Kamb for a glacier bed.

Reports

Andrews, D. J., A stochastic fault model (abs.): A.G.U. Fall Meeting, 1978.

Interactive Data Processing Center

8-9940-02085

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Investigations

The interactive data processing center provides investigators with a convenient state-of-the-art tool for studies of earthquake sources, wave propagation, ground response, and strong motion. Incoming data may be transferred from a variety of sources (digital, analog, film, etc.) to on-line disk packs for fast, multi-user access. Investigators are able to analyze their data using familiar, industry standard FORTRAN techniques. Results may be obtained either on a line printer, for textual information, or in a variety of graphic forms on CRT graphics terminals and digital plotters. The center also serves as the distribution center to investigators at other sites who are interested in obtaining copies of processed field data.

Results

The Ground Motion IDPC, consisting of a Digital Equipment Corp. PDP 11/70 minicomputer and peripherals, was installed in late July, 1978, and accepted August 4, 1978. Within the three months the system has been operating, data from several diverse experiments have already been processed to publication form. Examples include:

1. a set of high-frequency accelerograms of local earthquakes recorded in a deep South African gold mine;
2. high-dynamic range recordings of aftershocks of the Oroville, California earthquake;
3. five strong-motion recordings from the incredibly destructive 7.8 magnitude Tangshan earthquake in which 800,000 people were killed.

These raw data are first plotted on a Tektronix 4014 CRT and then operated on by any of several analysis packages such as Fast Fourier transforms or integration routines. When a set of plots is finalized on the 4014, a simple set of commands instructs the computer to regenerate the exact plots on an electrostatic plotter. Thus the center has merged the speed and flexibility of interactive computing with the quality of on-line electrostatic plotting.

Reports

None

SOURCE MODELS INFERRED FROM LONG AND SHORT PERIOD TELESEISMS FOR THE 1975 POCATELLO VALLEY AND 1968 BORREGO MOUNTAIN EARTHQUAKES

By

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Summary of Semi-Annual Technical Report for
27 February 1978 to 27 August 1978

OBJECTIVE

The objective of this research project is to determine the extent to which near-field strong ground motion is correlated with and constrained by the far-field data. The ultimate issue to be addressed is whether far-field data, particularly the short period records, can be used to infer the main characteristics of the strong motion source, at least in the common frequency band. Our research program to achieve this objective employs synthetic seismogram methods to model both the strong ground motion and the far-field ground motion. Our interest is primarily in the frequencies from 0.5 to 2.5 hz. These frequencies can be observed at large distances and are also of considerable interest for strong motion studies.

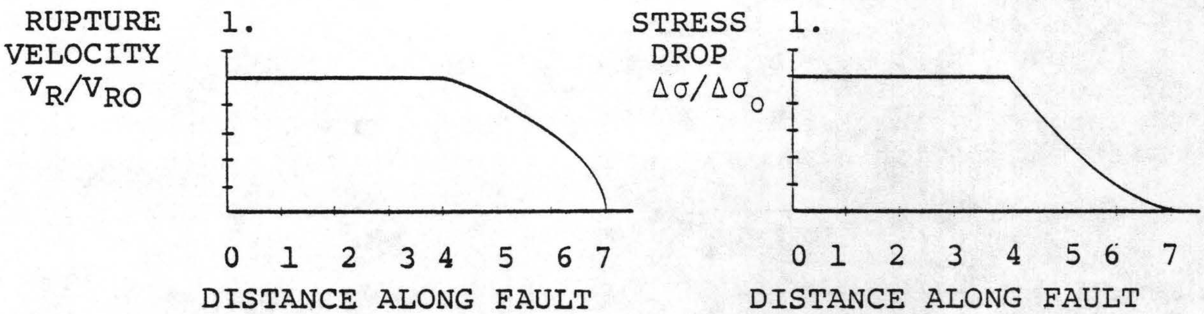
SUMMARY OF RESEARCH ACCOMPLISHED

During the first part of this program we have collected data on five earthquakes and begun a detailed study of two of them. The earthquakes chosen for study are three western U.S. events: (1) 1975 Pocatello Valley, (2) 1968 Borrego Mountain, (3) 1975 Oroville and two others; (4) 1976 Gazli and (5) 1977 Romania. One criteria for choosing the events to be studied is that they have good near- and far-field data. We also tried to select events for which some previous work was available (at least a fault plane solution) so we didn't have to start from the beginning to do our quite detailed study.

We began our studies with the Pocatello Valley and Borrego Mountain earthquakes. Although there are no near-field data for the Pocatello Valley earthquake, it is of interest because it is a large Basin and Range event which has received relatively little attention. The Borrego Mountain earthquake, on the other hand, has received considerable attention. However, our interest is in the short period records and no detailed studies of this data set have been published.

Our aim is to study these events in the same way that the San Fernando earthquake was studied in a previous contract (Bache and Barker, 1978). In that work, a source model was developed for the San Fernando earthquake that was consistent with the entire range of observations; the static data, far-field surface wave data, far-field long and short period body waves and the near-field strong motion data. The techniques used to infer this source model were used to investigate the Pocatello Valley and Borrego Mountain events.

In our study of the San Fernando event, it was found that in order to fit both long and short period data, the source model must include variable rupture velocity and stress drop. A similar result was found for the Pocatello Valley event. Simple models (constant stress drop and rupture velocity) which fit the amplitude and frequency content of the short period data have too small a moment. To simultaneously satisfy all data, a more complex model is required. The rupture velocity and stress drop as functions of position along the fault are shown below for our preferred fault model.



The initial values of rupture velocity and stress drop are V_{RO} = 3 km/sec and $\Delta\sigma_o$= 166 bars. The fault orientation was strike N45°E, dip 39°W, and plunge 53° up. The moment was 7.1 x 10^{24}dyne-cm which is consistent with earlier studies. The fault orientation and dimension are consistent with aftershock studies by Arabasz and co-workers.

We have also begun a study of the Borrego Mountain earthquake. Using long period body waves, Burdick and Mellman (1976) inferred a model for this event which was a point dislocation with a triangular time history. They also modified their source time function to fit the short period records at the WWSSN station WES by simultaneously deconvolving the short and long period records. To see whether this model fits the short period data for many azimuths, we computed synthetic seismograms. We find that the major features of the observed records are matched at most stations, though the fit is not as good as in our work on the San Fernando and Pocatello Valley events. However, the amplitude of the source is consistent with both long and short period data. We conclude that while some adjustments should be made to improve the fit to the short period records, the simple dislocation source provides a reasonable fit to both sets of data.

FUTURE PLANS

In studying the San Fernando and Pocatello Valley earthquakes we used the Archambeau/Minster relaxation model and concluded that variable stress drop/variable rupture velocity effects were necessary to explain the data. For the Borrego Mountain event a single dislocation time history consistent with short and long period data was inferred by Burdick and Mellman. It's not clear whether a constant rupture velocity and stress drop source will give this time history. We also need to determine whether the Borrego Mountain earthquake is different from the others as far as this aspect is concerned. We plan to carefully study our results for these events, interchanging source models to delineate the extent to which our conclusions are model dependent.

In the remainder of the contract we intend to look at two, or perhaps three, other events using the same techniques. These are the 1975 Oroville and the 1977 Romania earthquakes. If resources permit, we also would like to study the 1976 Gazli earthquake. For all the events studied, we will be addressing the implications of our results for the near-field strong ground motion.

Dynamic Soil Behavior

8-9550-01630

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Investigations

1. Continued a parametric study on the use of available stress-strain relations in nonlinear and equivalent-linear ground-motion computations.

2. Continued laboratory testing and data interpretation of the one-dimensional dynamic behavior of San Francisco Bay mud.

3. Continued laboratory testing of the three-dimensional dynamic behavior of San Francisco Bay mud.

4. Initiated an analytical study on the torsional response of cylindrical soil samples.

Results

1. An interactive data analysis program with plot routines has been developed for use with resonant column tests.

2. In addition to resonant column and torsional simple shear tests, consolidated-undrained and consolidated-drained triaxial tests have been performed on samples of San Francisco Bay mud. Results from these tests indicate that the shear modulus of San Francisco Bay mud is somewhat strain-rate dependent. At a shearing strain of 0.01 percent, the modulus increases by about 7 percent for each order of magnitude increase in strain rate for cycling between 0.1 Hz and 100 Hz.

3. A loading system capable of generating any combination of the three-dimensional cyclic stresses to the cubical test cell has been developed. This system consists of three levers driven by cams that were designed to produce a sinusoidal pressure. The pressure is supplied by a mercury pot suspended at the end of each level.

Reports

Joyner, W. B., and Chen, A. T. F., 1978, Seismic site response of nonlinear soil media, a discussion: Journal of the Geotechnical Division, American Society of Civil Engineers (in press).

Ko, H. Y., 1978, Site characterization for plastic and strain-softening analyses: (invited paper) Workshop on Site Characterization, Northwestern University, June.

Lodde, P. F., 1978, Shear moduli and material damping ratio of San Francisco Bay mud: University of Texas M.S.C.E. thesis.

Seismic Wave Attenuation in Conterminous United States

8-9950-01205

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Investigations

1. Continuation of data reduction and analysis of seismograms for another 13 earthquakes recorded by the Long Range Seismic Measurement Stations (LRSM) in different geological environments in the U.S. is in progress.

2. Continuation on the attenuation study of short-period waves from 29 earthquakes recorded on strong-motion instruments in the U.S. is in progress.

3. Continuation of regional compilation of seismograms for selected small events in the U.S., to be used in the regional seismic-wave attenuation study, is in progress.

4. Developed a software package for data retrieval and display of the accumulated reduced data base obtained from the LRSM stations.

5. Data reduction and analysis of 81 NTS events for the following phases P_n, P_g, and Lg is underway.

6. Further work is being done on the investigation of the possible conceptual extension, using computer applications, of evaluating M_o (earthquake moment) from strong-motion recordings.

7. Continuation of the investigation of the decay of short-period seismic signals with distance and depth is being pursued, using a theoretical surficial earth model. This study takes into consideration variations of the source-time function and depth.

Results

1. Attenuation curves for ten historical U.S. earthquakes have been constructed. These curves show particle velocity (cm/s) as a function of distance, with the Modified Mercalli Intensity ratings as a parameter. These curves will assist the user (engineer, seismologist, etc.) in determining the level of ground motion in different regions of the U.S.

2. A family of curves has been developed for horizontal particle velocity (cm/s) as a function of epicentral distance (km), with M_L as a parameter. Curves for $5 \leq M_L \leq 8$ are given. From all the recorded strong-motion particle velocity recordings, only 11 percent do not fit the set of curves. A magnitude scaling law that accompanies the above curves has been derived.

3. Preliminary attenuation curves have been derived for the Northeast U.S. (New England), using local earthquakes and quarry blasts recorded by the Northeastern U.S. Seismic Network. Further work on this study is in progress.

4. Preliminary attenuation curves for Lg in the Midwest have been derived, using small magnitude earthquakes recorded by the St. Louis University network. Further work on this study is in progress.

5. Study of the attenuation of a newly proposed instrumental intensity has been extended to obtain the intensity in the velocity- and displacement-time domain. It has been evaluated using recordings from different magnitude earthquakes and it has been correlated with other ground-motion parameters and with other instrumental intensities. One of the main results in this study is that our proposed instrumental intensity has less scatter than any previously proposed instrumental intensities. Also, the procedure in evaluating this instrumental intensity is rather simple and can be duplicated with a 10 percent variation in the final results. Further work on this study is in progress.

Reports

Berrocal, J., Espinosa, A. F., and Galdos, J., 1978, Seismological and geological aspects of the Mantaro landslide in Peru: NATURE, v. 275, No. 5680, p. 533-534.

Espinosa, A. F., 1978, Metodologia sismica de la microzonificacion e inconsistencias de la escala modificada de Mercalli [abs.]: Seminar on Urban Seismic Microzonification, Lima, Peru, Oct. 20-27, 1978.

Espinosa, A. F., and Zambresky, Liana, 1978, Attenuation curves for ten historical earthquakes in the United States, (in preparation).

Regional Shear Wave Studies

8-9940-02087

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Investigations

1. Investigate dependencies of measured site amplification, observed 1906 earthquake intensities, and physical properties of near surface geologic units on downhole seismic velocity logs, to develop generalized guidelines for predicting earthquake ground motions on a regional scale. These studies are designed to develop improved methodologies for seismic zonation of the San Francisco Bay region.

2. Collect seismic velocity data, physical property data, and geologic data in drill holes to develop an improved data base for seismic zonation of the metropolitan Los Angeles Basin.

3. Compare San Francisco Bay Regional shear wave velocity data to Los Angeles data to determine the significant parameters for extrapolating 1906 San Francisco intensity data to the Los Angeles region.

4. Investigate dependencies of measured site amplification in the Los Angeles region using downhole shear-wave velocity measurements and geologic logs.

Results

1a. Seismic wave velocities measured at 59 sites in the San Francisco Bay region have been compared with several readily determined physical properties of the materials. Shear wave velocity was found to correlate with these properties more strongly than P-wave velocity. Correlations obtained suggest a classification scheme useful in defining seismically distinct geotechnical units.

b. Six seismically distinct units have been determined from the sedimentary deposits in the San Francisco Bay region (Table 1).

TABLE I

SHEAR WAVE VELOCITIES IN GEOLOGIC MATERIALS

Distinct Seismic Units	Physical Properties	Shear Wave Vel. (m/s) Mean	Std. Dev.	Amp. (Pred.)	Intensity Increment (Pred.)
		Sedimentary Deposits			
I	Clay-Silty Clay very soft-soft ($N \leq 4$)	88	22	11.43	2.01
II	Clay-Silty Clay medium-hard ($N \geq 4$)	186	22	7.73	1.75
III	Sandy Clay-Silt Loam Interbedded Coarse and Fine Sediment	265	32	5.97	1.53
IV	Sand loose to dense ($N \leq 40$)	206	36	7.22	1.69
V	Sand dense to very dense ($N \geq 40$)	366	84	4.38	1.26
VI	Gravel	504	138	2.79	.89

c. Seven seismically distinct units have been determined for bedrock materials in the San Francisco Bay Region (Table II).

TABLE II

SHEAR WAVE VELOCITIES IN GEOLOGIC MATERIALS

Distinct Seismic Units	Rock Type	Physical Properties Hardness	Fracture Spacing	Shear Wave Vel. (m/s) Mean	Std. Dev.	Amp. (Pred.)	Intensity Increment (Pred.)
			Bedrock Materials				
I	Sand- stone	Firm to Soft	Moderate and wider	470	48	3.14	0.98
II	Igneous Sedi- mentary	Hard to Soft	Close to very close	577	51	2.12	.69
III	Igneous Sand- stone Shale	Hard to Firm	Close	751	46	.82	.22
IV	Igneous Sand- stone	Hard to Firm	Close to Moderate	923	48	-.20	-.24
V	Sand- stone Conglom- erate	Firm to Hard	Moderate and wider	1073	31	-.95	-.65
VI	Sand- stone	Hard to quite firm	Moderate and wider	1257	42	--	--
VII	Igneous	Hard	Close to Moderate	1660	20	--	--

d. Amplification and Intensity increments were predicted on the basis of shear wave velocity for the seismically distinct units using the empirical relations

$$AMP = -11.4 \log (SVEL(m/sec)) + 33.6$$

and

$$\delta I = -0.0027 (SVEL(m/sec)) + 2.25$$

2. Twenty seven locations have been drilled (usually to a depth of 30 m, one hole to 55 m) and logged for shear and compressional wave velocities in the Los Angeles area. Geologic logs determined from drill cuttings and examination of samples have been prepared from each location. These logs are a first step in development of a regional data base for seismic zonation of the Los Angeles area.

3. Investigation in progress.

4. Investigation in progress.

Reports

Gibbs, J. F., Fumal, T. E., and Borcherdt, R. D., 1978, In-situ measurements of seismic velocities at 59 locations in the San Francisco Bay region. Abstract, SSA, April 6-8, Sparks, NV.

Fumal, T. E., Gibbs, J. F., and Borcherdt, R. D., 1978, Correlations between shear-wave velocities and physical properties of near-surface geologic materials in the southern San Francisco Bay region. Abstract, SSA, April 6-8, Sparks, NV.

Numerical Modeling of Ground Motion

8-9940-01896

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Investigations

1. Develop a hybrid finite element-finite difference method for modeling wave propagation problems.

2. Apply this method to actual data to determine how well the modeling method behaves.

Results

1. A variety of methods are available for use in modeling seismic wave propagation in elastic media. A broad classification scheme might begin by separating dynamic finite element methods that use the standard matrix differential equation:

$$(K)u + (C)\dot{u} + (M)\ddot{u} = F \tag{1}$$

and finite difference methods that approximate the elastic equation:

$$\frac{\rho\partial^2 \upsilon}{\partial t^2} = (\lambda+\mu)\ \nabla\ (\nabla\cdot\upsilon) + \nabla^2\upsilon_J \tag{2}$$

where (K), (C), and (M) are stiffness, damping, and mass matrices, respectively; υ is a vector of displacement; ρ is the density; λ is the first Lame parameter; and μ is the rigidity. Although researchers in geophysics have traditionally tended to develop exclusively finite difference or finite element models, a hybrid scheme utilizing both methods in the same model has some desirable features, including the maintenance of sharp velocity contrasts between distinct media. Indeed, such a hybrid approach has been numerically implemented for models containing 90° interface corners, and extensions to a wider variety of subsurface geometries are currently being undertaken.

2. Explicit finite difference formulations, like the axi-symmetric layer over half-space and the plane-strain heterogeneous model, have been modified by the insertion of finite elements into immediate neighborhoods of sharp velocity contrasts and corners, corresponding to areas where distinct rock formations are in contact. For example, a diagonal ramplike interface has been surrounded by finite elements, as in Figure 1.

3. Finite element treatment of interfaces compares favorably, in terms of computation time, to the pure finite difference method of constructing, adjacent to material interfaces, fictitious layers whose properties result from the equating of displacements and normal and tangential stresses across the interfaces. Numerical results from the hybird model have been compared to results obtained using the heterogeneous finite difference model. Finally, an absorbing boundary has been fitted into the models using two sets of boundary

conditions at each time step and averaging the resulting solutions at the boundaries.

Reports

Harding, S. T., Carver, David, Henrisey, R. F., Dart, R. L., and Langer, C. J., 1978, The Scurry County, Texas, earthquake series of 1977-1978: induced seismicity? [abs.]: Seismological Society of America, Program and Abs., 50th Ann. Meeting, Eastern Section, October 16, 17, 18, 1978, Weston Observatory, Weston, Mass.

Harmsen, S. C., and Harding, S. T., 1978, Hybrid wave-propagation model [abs.] Seismological Society of America Abstract.

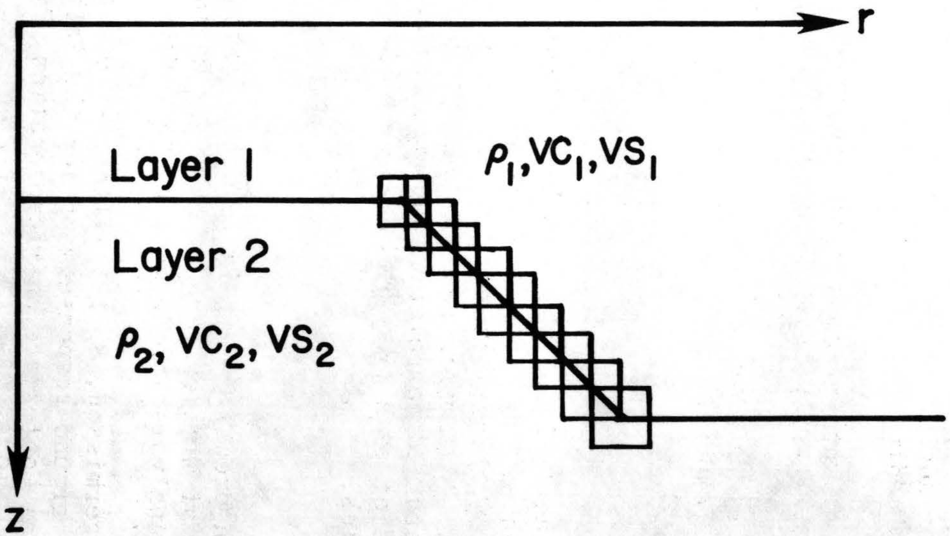

Figure 1.--Fitting finite elements next to a diagonal ramp. ρ_i, VC_i, VS_i = density, compressional speed, and shear speed, respectively; i = 1, 2.

Ground Response, Salt Lake City, Utah Region

8-9940-01919

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Investigations

1. Acquisition of nuclear-explosion ground motion data at 18 sites in the Ogden area and 10 additional sites in the Salt Lake City area.

2. Continuation of data processing and analysis of ground motion data acquired in the Ogden-Provo-Salt Lake City area.

3. Continuation of an inventory of structures other than single-family dwellings in the corporate Salt Lake City area.

Results

Preliminary analysis of the broadband ground-motion data acquired in the Provo area shows that the ground response is significantly greater at sites underlain by thick, water-saturated, unconsolidated materials than at sites on rock. A similar result has been obtained in the Salt Lake City area. A detailed correlation between ground response and the physical properties of each site is lacking at this time and is the subject of current studies.

Reports

Hays, W. W., (in press) Uncertainties in seismic input and site response: Proceedings of Mini-conference on Civil Engineering and Design, Sessions on Seismic Analysis and Design, Boston, Mass., April 1979, 30 p.

Hays, W. W., Algermissen, S. T., Miller, R. D., and King, K. W., (in press) Preliminary ground response maps for the Salt Lake City, Utah area: 2nd International Conference on Microzonation, Proceedings, San Francisco, Calif., Nov., 1978, 12 p.

Ground Motion Modeling and Prediction

8-9940-01168

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Investigations

1. Shallow refraction profiles and downhole P and S velocity surveys in the Cholame area to provide additional data for modeling the strong motion records from the Parkfield-Cholame earthquake (R. E. Warrick, R. M. Hazlewood and W. B. Joyner).
2. Analysis of data from downhole P and S velocity surveys in young sediments in the San Francisco Bay Area. (R. E. Warrick and W. B. Joyner).
3. Statistical analysis of strong motion data (D. M. Boore, A. A. Oliver, III, R. A. Page, and W. B. Joyner).

Results

1. One 7200-foot and two 5000-foot reversed refraction profiles have been shot in the Cholame area. Preliminary examination of the data indicates that it will be possible to map the base of the young Quaternary alluvium with confidence.

Reports

Boore, D. M., Oliver, A. A., III, Page, R. A., and Joyner, W. B., 1978, Estimation of Ground Motion Parameters: U.S. Geol. Survey, Open-file report 78-509, 86 p.

Semi-Annual Technical Report

1 January 1978 to 30 June 1978

APPLICATION OF EARTHQUAKE MECHANISM STUDIES TO PREDICTION OF LONG-PERIOD GROUND MOTION AND RELATED PROBLEMS

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Summary

The local magnitude M_L is determined from strong-motion accelerograms. An average value of $M_L = 7.2$ is obtained for the 1952 Kern County earthquake which is significantly smaller than the commonly used value of 7.7. The local magnitude, M_L, has direct relevance to engineering applications because M_L is determined within the period range of greatest engineering interest (0.3 to 2 sec). The values of M_L determined for major earthquakes at several distances indicate very little dependence of M_L on the distance (Figure 1). These results can be used to empirically predict the amplitude of near-field ground motions.

An empirical approach to the synthesis of long-period ground motions has been investigated. A recent analysis of strong-motion and seismoscope records suggests that the Guatemala earthquake and the Borrego Mountain earthquake have about the same M_L (local magnitude) indicating that the Borrego Mountain earthquake and the individual event of the Guatemala earthquake are of about the same size at periods around 1 sec. This result suggests that long-period ground motions produced by a Guatemala type earthquake may be empirically predicted by convolving the appropriately scaled ground motion produced by the Borrego Mountain earthquake with the source time sequence of the Guatemala earthquake. Preliminary analyses showed that the

amplitude of long-period ground motion is comparable to that of the A-1 design earthquake, but the duration can be much longer than that of the design earthquake.

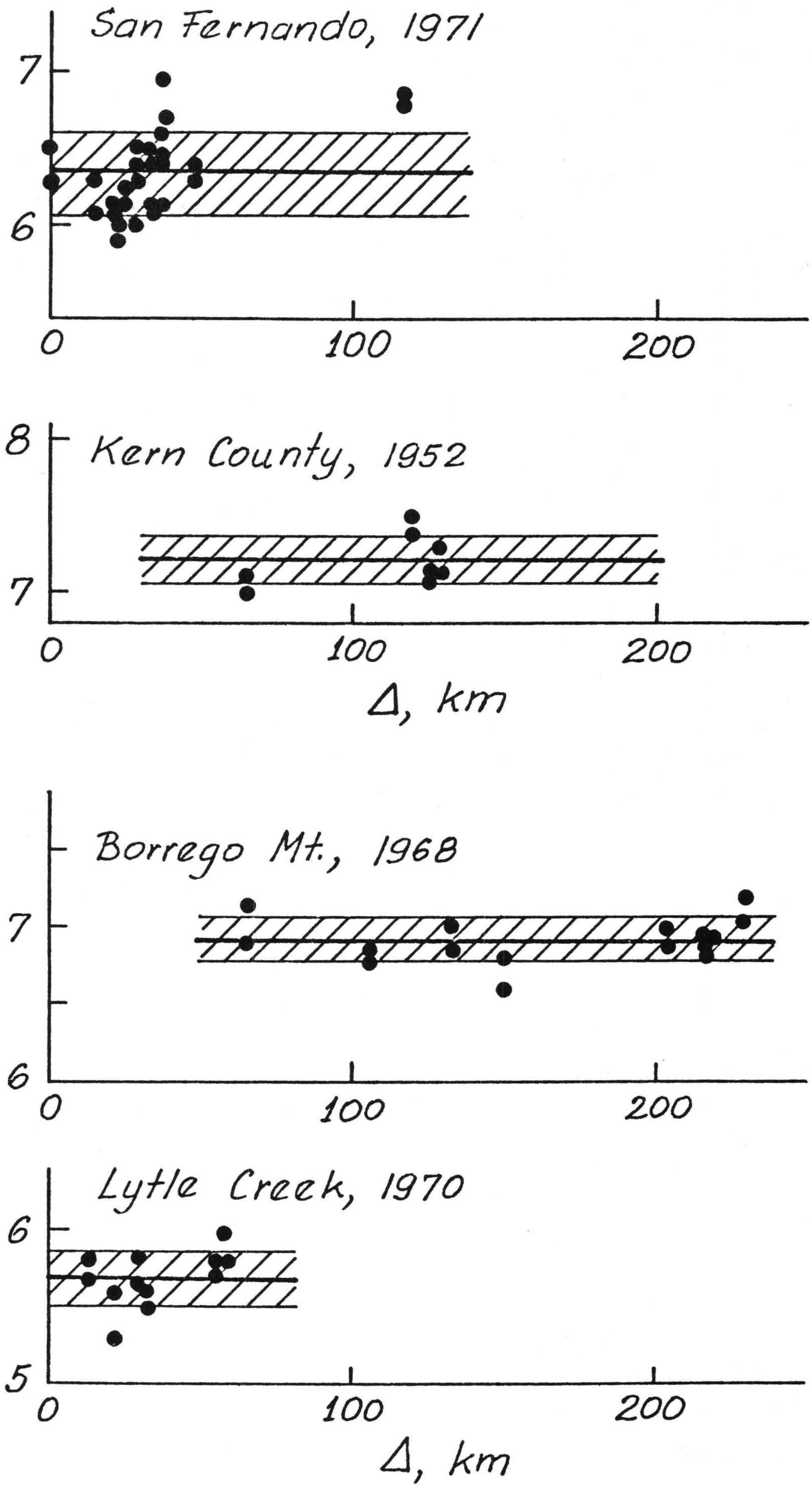
San Fernando, 1971
7
6
0
100
200
Kern County, 1952
8
7
0
100
200
Δ, km
Borrego Mt., 1968
7
6
0
100
200
Lytle Creek, 1970
6
5
0
100
200
Δ, km

Fig. 1

Data Acquisition in Support of Ground Motion Projects

8-9940-02091

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Investigations

1. Los Angeles, California - Ground motions from two nuclear events were recorded at 18 sites to continue the study of ground response in this area. Some of the sites were reoccupied to verify repeatability of site transfer functions.

2. Salt Lake City - Ogden - Provo, Utah - Ground motion from several nuclear events were recorded at 31 new sites and 16 former sites in the Salt Lake City - Ogden - Provo area. These data are being used in the continuing study of ground response.

3. Idaho - Seismic background and ground motions were recorded at 13 sites from an 8,000 lb. HE in the southern part of the Snake River Plain. Eight sites were occupied by portable seismic systems to record a 7,000 lb. HE on the northern part of the Snake River Plain. The data are being analyzed to define attenuation characteristics in the area and to determine the sensitivity of attenuation to azimuthal changes.

4. Parker Dam, Arizona - Several seismographs sites were located on and in the Arizona irrigation tunnel for a Corps of Engineers HE event. The event was not a total success; therefore, the data are not useful.

Results

The emphasis during the past 6 months has been primarily on obtaining data from nuclear explosions or targets of opportunity such as the Snake River Plain. These data are being processed and analyzed by A. Rogers, W. Hays, and K. King.

Reports

Hays, W. W., Algermissen, S. T., Miller, R. D., and King, K. W., Preliminary evaluation of ground response, Salt Lake City, Utah area: 2nd International Conference on Microzonation Proceedings, San Francisco, Calif., Nov. 1978, 12 p. (in press).

THE ROLE OF ANELASTICITY IN EARTHQUAKE GROUND MOTION

Grant No. 14-08-0001-G493

T.V. McEvilly, L.R. Johnson, W.J. Silva
University of California, Berkeley

SUMMARY

This report summarizes research aimed at understanding the role that anelasticity plays in strong ground motion due to local earthquakes. It centers around data collected at the Richmond vertical array of strong ground motion accelerometers.

Soil samples taken from a borehole at the Richmond array have been analyzed in the laboratory in terms of their elastic and anelastic properties. For shear waves in the frequency range of 10 to 60 kHz, these samples show phase velocities in the range of 100 to 120 m/sec and quality factors in the range of 2 to 20. There is a suggestion that the quality factor may contain oscillations as a function of frequency.

The accelerometer records obtained at the Richmond array from a magnitude 4.3 local earthquake at a distance of 13 km have been analyzed in terms of near-vertically traveling body waves. Using transfer functions calculated with a formulation which is exact even for highly attenuating media, records obtained in bedrock at a depth of 120 feet have been propagated to the surface assuming the energy consists primarily of near-vertically incident S waves. A comparison with the accelerometer records observed at the surface demonstrates some success in this modeling exercise, particularly with respect to the degree of attenuation imparted by the soils. However, the analysis also suggests that a significant portion of the motion at the surface is due to lateral propagation.

Topical Studies in Seismic Risk

8-9950-01733

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Investigations

1. A new computer program for seismic risk analysis was developed to account for rupture lengths of earthquakes; uncertainties in all important variables that affect seismic hazard calculations are considered.

2. The duration of strong ground motion was investigated with the purpose of using it in conjunction with peak-motion amplitudes to define the destructiveness of seismically induced shaking.

3. Using a new method, which accounts in preliminary fashion for the destructiveness of large-magnitude earthquakes and which uses a liquefaction-damage function that has been proposed by Japanese colleagues, the probability of liquefaction accuracy at a site located on Tokyo Bay was determined.

Results

1. Bayesian uncertainties in seismological and geophysical parameters can be accounted for in seismic hazard analyses simply by using, in many instances, the Bayesian estimate for a parameter. This results from the almost linear relationship between these parameter values and calculated risks. Of course, for the full Bayesian distribution of risk (or peak-motion values at a given risk level) the distribution of parameter values must be used.

2. When earthquake motions have been recorded, the duration of strong shaking (using any of several definitions) is often useful to estimate nonlinear damage induced in mathematical structural models. That is, if two records are obtained at the same distance from similar magnitude events, and the same peak amplitudes are recorded, the record with the longer duration induces more damage in nonlinear models. But it is not possible to predict (with much accuracy) the duration of motion, given magnitude and distance, and the nonlinear damage is much more strongly dependent on peak-motion amplitudes than it is on duration. Thus to predict damage (rather than to explain it after an earthquake), duration does not seem to be a useful parameter. This result seems to be counterintuitive, primarily because our intuition has been "confirmed" by records which fit preconceived notions (short, impulsive records, for example, from the Parkfield earthquake, give large amplitudes, short durations, and little damage; and long vibratory motions, for example, during the 1964 Alaska earthquake, give low, estimated amplitudes of acceleration but cause extensive damage). Despite these ostensibly confirming examples, there are many records in the available California data set that yield opposite conclusions; that is, records obtained at small distances from low-magnitude earthquakes

indicate large damage, and records obtained at long distances from large-magnitude earthquakes indicate less damage, even for the same observed peak amplitudes. Thus, statistical averaging over the entire data leads to the conclusion that estimating duration in addition to observing peak amplitudes will not lead to more refined damage estimates or design levels than using peak amplitudes alone. Of course this result depends on the simple description of input assumed here (magnitude, distance, and site conditions), and is valid only for the simple damage function used (hysteretic energy input to a bilinear structural model). Results for more elegant ground-motion models await the development of these models by geophysicists.

3. For calculating probabilities of liquefaction, use of the damage criterion proposed by Japanese colleagues leads to a simple scaling of probabilities for each magnitude and distance, and thus a scaling of the marginal probabilities. Including a function proposed by Seed for the "number of cycles" of motion versus magnitude does not radically alter the estimation of liquefaction as a function of magnitude and distance. However, this estimate does differ substantially from empirical observations of liquefaction (see attached figure), for reasons not yet well understood. Either observed liquefaction effects are not consistent at different magnitudes and distances or the mathematical models of shear stress traditionally used by soils engineers are inadequate. Further work is planned to resolve this problem.

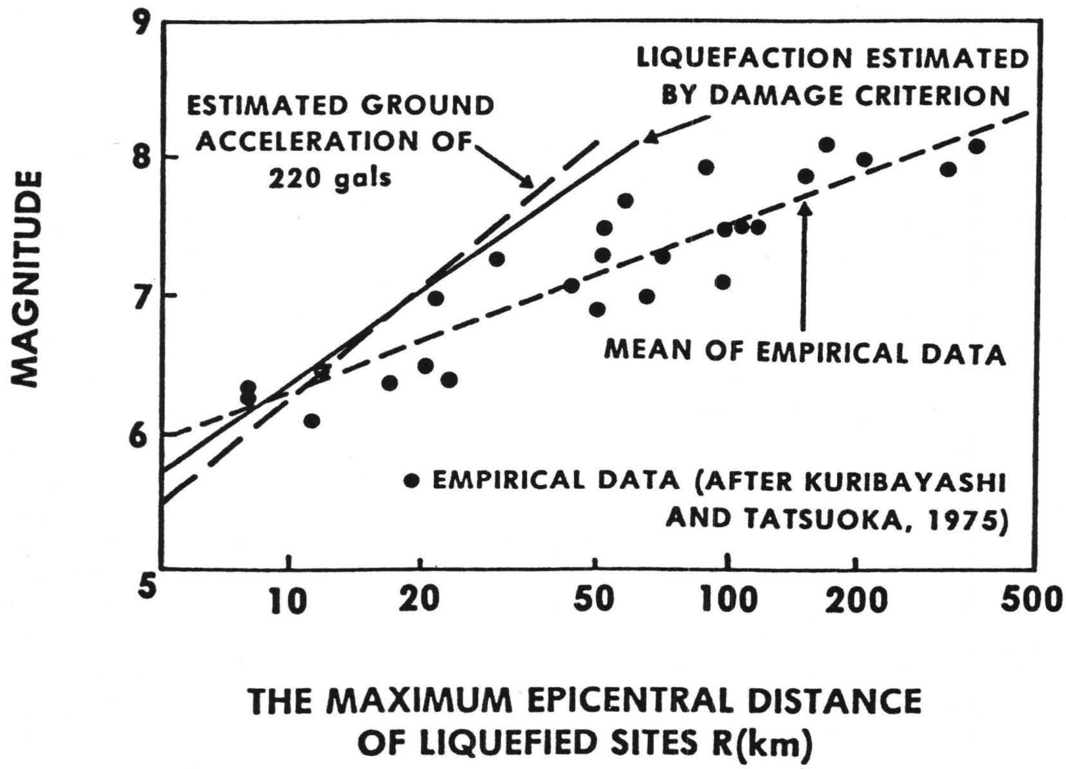

Figure 1.--Magnitudes and distances leading to liquefaction in 3-m deep layer, from empirical data and damage criterion. R, epicentral distance

Reports

McGuire, R. K., Frisk: Computer program for seismic risk analysis using faults as earthquake sources: U.S. Geological Survey Open-File Report 78-1007, 73 p. (In TRU.)

McGuire, R. K., Effects of seismological and geophysical uncertainties on probabilistic seismic hazard calculations: American Society of Civil Engineers, Specialty Conference on Probabilistic Mechanics and Structural Reliability, January 10-12, 1979. Tucson, Arizona. (In TRU.)

McGuire, R. K. Tatsuoka, F., Iwasaki, T., and Tokida, K., 1978, Empirical and analytical methods of estimating soil liquefaction risk: U.S.-Japan Panel on Wind and Seismic Effects, 10th Joint Meeting, May 22-26, 1978, Washington, D.C., Session IV, 11 p.

McGuire, R. K., Tatsuoka, F., Iwasaki, T., and Tokida, K., Assessment of the probability of liquefaction of water-saturated, reclaimed land: Third International Conference on Applications of Statistics and Probability, Sydney, January 1979, Proceedings.

Earthquake Intensities and Recurrence
8-9940-01784

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INVESTIGATIONS

1) Continued the compilation and organization of damage data of the 1906 California earthquake by localities from the official reports and from newspapers and books.

2) Assigned seismic intensity values to the 1906 earthquake damages using both existing intensity scales and a revised intensity scale.

3) Tabulated and graphically plotted the 1906 intensity data with regard to distance from the fault and local geologic setting.

4) Prepared and circulated the map of expected seismic intensities in the Los Angeles region for a great earthquake on the nearby San Andreas fault, using the 1906 earthquake intensity pattern.

5) Investigated the damages and seismic intensities of the 13 August 1978 earthquake at Santa Barbara, California.

RESULTS

1) The compilation of damages by localities provides major improvement of seismic intensity information compared with the published intensity maps of the 1906 earthquake.

2) The seismic intensity pattern of the 1906 earthquake shows that almost all localities on alluvium and most localities on bedrock had intensity VIII or greater out to distances of about 80 km from the fault, and that no locality beyond 80 km from the fault had intensity VIII. This intensity pattern may be the result of subsurface seismic refraction processes.

3) Ground failures such as liquefaction also occurred at distances of about 70 km from the fault.

4) Except for ground failures, there was not a large difference of seismic intensities on alluvium versus bedrock (except for a "size of community" effect).

5) The Expected Intensity map of the Los Angeles region for a major earthquake on the San Andreas fault, based on the detailed 1906 damages, indicates that significant building damages would occur in the northern part of the Los Angeles basin, including some fall of brick walls into streets, fall of chimneys, and possible collapse of unusually weak brick buildings.

6) At the 13 August 1978 Santa Barbara earthquake, the seismic intensity in downtown Santa Barbara, near the epicenter, was less (VI-VII) than at Goleta (VIII), which is farther from the epicenter but near to the terminal end of the earthquake fault rupture (as shown by aftershocks). This is a clear example of the importance of the fault rupture on intensity patterns.

Expansion of PDP-11 for Digital Input

8-9940-02088

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Investigations

1. Expand PDP 11/40 system to include input of digital cassette recordings and interactive graphic data processing.

2. Develop and modify software for digital (as opposed to hybrid) data processing utilizing interactive graphics.

Results

1. A microprocessor (PDP-11-03) and a software package for down-loading programs and for controlling the 11-03 from the 11-40 has been acquired.

2. A Tektronics 4014-1 graphics system has been acquired and software development is underway.

3. Plans have been made to borrow cassett tape units from Menlo Park for the development of a general data unblocking and formatting software for reading the various types of field recorded cassett tapes.

4. Figure 1 shows the present system configuration with interfacing with Branch of Global Seismicity computers indicated.

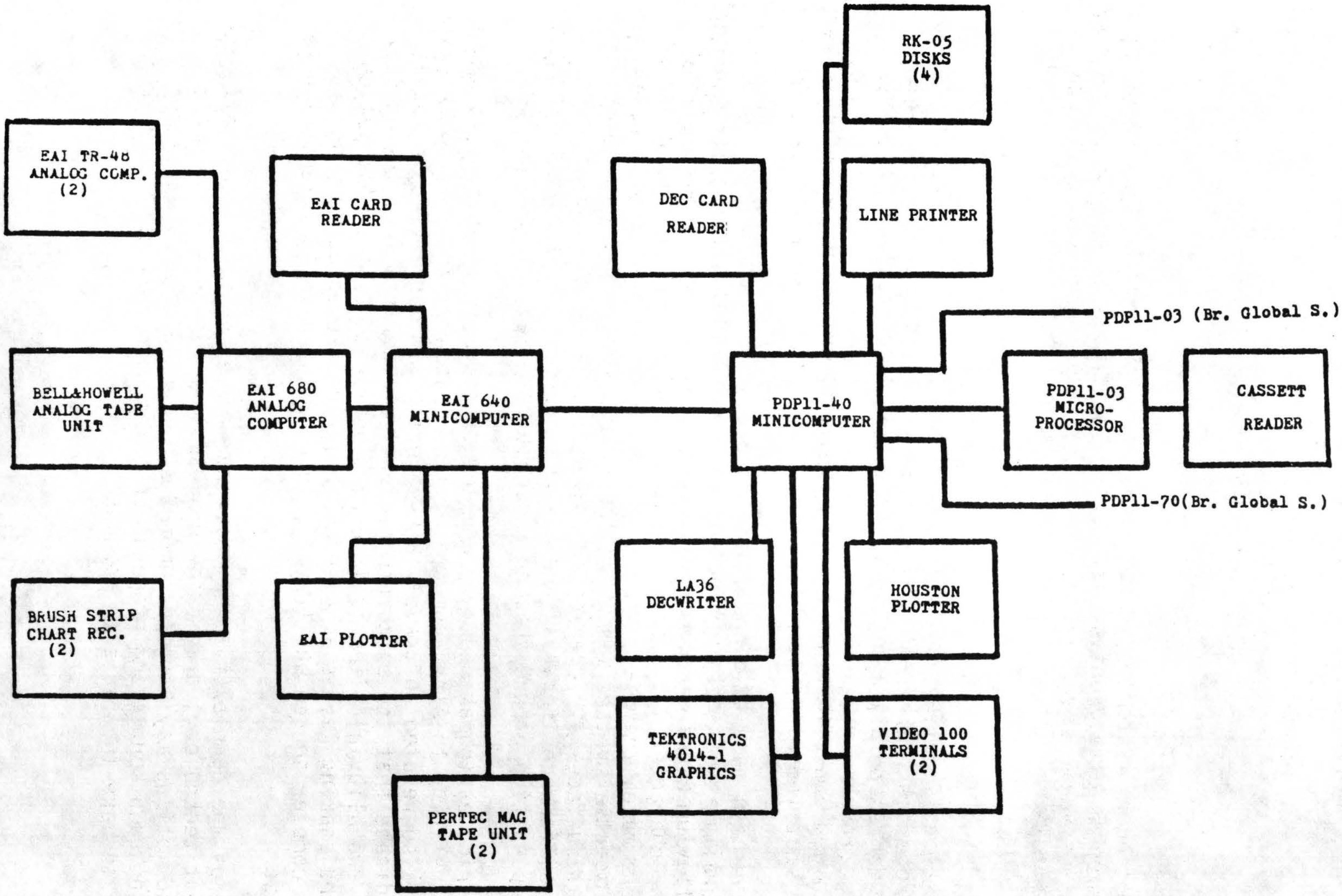

Figure 1.--Golden Processing Center

Seismic Zonation Studies in Los Angeles Basin

8-9940-01730

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Investigations

1. Ground motion produced by the 1971 San Fernando earthquake was compared to that accompanying Nevada Test Site nuclear explosions, using recordings of both events at several common stations in the San Fernando Valley-Pasadena area of California.

Results

1. Average spectral ratios at sites underlain by thin-to-intermediate thickness alluvium indicate that for both nuclear and earthquake ground motions, spectral amplitudes on alluvium are greater than on rock (sedimentary or crystalline) across most of the period range of engineering significance. Also, long-period amplification at a site underlain by intermediate-thickness alluvium was observed to be higher than that at a site underlain by thin alluvium.

2. The general agreement between long-period earthquake and nuclear spectral ratios at alluvium sites indicates that surface waves develop with similar amplification characteristics for both nearby and distant sources at these sites. In one case, the lack of agreement at long periods between earthquake and nuclear spectral ratios for a site underlain by shallow sedimentary rock suggests that surface-wave development at this site reflects some wave-propagation differences for near and distant sources. This effect produces slightly conservative ground shaking response estimates at long periods.

3. Short-period earthquake energy recorded at Old Seismo Lab appears anomalously high relative to Athenaeum and Millikan Library, and this observation is possibly also related to travel-path effects. If correct, this result does not indicate that the site response estimate derived from the nuclear data at the two alluvial sites is in error, but suggests that estimation of actual ground shaking levels at sites near earthquake epicenters should incorporate complex source and travel-path geometry effects in addition to site response.

4. Because of the complexity of predicting source and travel path effects using present technology, prediction of mean site response using nuclear event ground motions may have to incorporate some additional variance related to unknown source and propagation effects to correctly represent expected earthquake-induced site response.

Reports

Rogers, A. M., W. W. Hays, 1978, Preliminary evaluation of site transfer functions developed from earthquakes and nuclear explosions: Second International Conference on Microzonation, San Francisco, California.

CALIFORNIA DIVISION OF MINES AND GEOLOGY

CLASSIFICATION AND MAPPING OF QUATERNARY SEDIMENTARY DEPOSITS FOR PURPOSES OF SEISMIC ZONATION, SOUTH COASTAL LOS ANGELES BASIN, ORANGE COUNTY, CALIFORNIA

by Edward C. Sprotte and David R. Fuller

U S G S GRANT NO. 14-08-0001-G-511

SUMMARY REPORT COVERING PERIOD FEBRUARY 9, 1978 TO AUGUST 8, 1978

The objectives of this investigative project are, over a 3 year period, to collect and interpret subsurface data to delineate the areal extent, subsurface configuration and physical characteristics of Quaternary sediments within the study area and to determine the expected ground response of these discriminated sediments to seismically induced ground shaking. During the initial period of the investigation subsurface data have been collected, orthophoto base maps have been prepared to display the location and types of data collected and electronic data processing capability to store, retrieve and display collected data is being developed.

Subsurface information collected includes data from highway bridge borings, water wells, oil wells, engineering investigations of building sites and soil surveys. Data base index maps have been prepared by mosaicking 7 1/2 minute U.S. Geological Survey orthophoto quadrangle maps; map scale is 1:24,000. Electronic processing program development to establish a Lithologic Properties Record of subsurface data collected appears to be feasible and is being developed.

SEISMIC RESPONSE MAPPING OF ST. LOUIS COUNTY (Pilot Study)

Richard W. Stephenson
John D. Rockaway

University of Missouri-Rolla
Rolla, Missouri 65401
October 23, 1978

INTRODUCTION

It is the objective of this research to provide the data necessary to define the magnitude of seismic risk and the nature of seismically associated geological hazards in a selected portion of St. Louis County (Creve Coeur), and to present these data in a form useful to those public and private officials involved in land-use planning.

PHASE I

The research is being carried out in two phases. The objectives of Phase I are to identify the local geologic conditions: soil and bedrock distribution and stratigraphy, the local tectonic system and its relationship with the regional tectonic framework, and the response of these materials to earthquake induced rock motions. In order to accomplish the goals of Phase I, the following principles and technique are being utilized: Field exploration, Laboratory testing and mathematical modeling.

Stage I--Field Exploration

The major objectives of this stage have been successfully completed. High quality soil specimens have been obtained for standard and dynamic laboratory testing and the local geologic conditions have been investigated. The soil stratigraphy, depth to bedrock, ground water elevation and relative density of cohesionless deposits were determined.

Stage II--Determination of Earthquake Induced Bedrock Motion

A principle activity conducted in the Phase I portion of the study has been the literature review and collection of published and unpublished data pertinent to the study. This study had the goal of determining the sustained horizontal acceleration and predominant period of motion for a design earthquake in the St. Louis region.

The Creve Coeur Quadrangle is approximately 100 miles (161 km) from the hatched boundary of region 1 or the New Madrid fault zone. The design earthquake for this region is of body wave magnitude 7.2 which is equal to the magnitudes of the three largest 1811-1812 earthquakes.

Examination of a typical accelerogram shows a wide range of periods is involved in the ground motion. The frequency characteristics of the induced ground motion will also change with increasing epicentral distance. High frequency components of the ground motion are attenuated more rapidly than the low frequency components. The frequency characteristics are also dependent on the earthquake magnitude, so that the dominant spectral composition shifts to the low frequency end of the spectrum with an increase in magnitude. In deneral, the predominant ground motion period at Creve Coeur from a "New Madrid" type earthquake will be in the low frequency end of the spectrum.

The relation between particle velocity and MM intensity has enabled Nuttli (1972, 1973a) to estimate ground motion in the Central U.S. From his examination of newspaper accounts of the effects of ground shaking at St. Louis, Nuttli (1973a) originally estimated the intensity to be MMI VII - VIII. This estimate did not take into account the amplifying effects of the underlying alluvial material and Nuttli has since lowered the intensity for St. Louis to MMI VII.

Nuttli's (1973) estimate of resultant sustained acceleration for a New Madrid fault zone design earthquake at a distance of 100 miles is 0.056 g. Assuming a factor of 2.5 to go from the vertical to horizontal acceleration, this gives a sustained resultant horizontal acceleration of 0.06 g.

Algermissen and Perkins (1976) have presented attenuation curves and a probabilistic bedrock acceleration map for the U.S. The attenuation curves for the eastern U.S. are from attenuation rates developed by Nuttli (1973a). Using a $m_b = 7.2$ earthquake at a distance of 100 miles gives a peak horizontal acceleration of 0.065 g. Examination of the probabilistic bedrock acceleration map shows the Creve Coeur area at about 0.073 g. This peak horizontal acceleration has a 10% probability of being exceeded in 50 years and is therefore a conservative estimate.

The sustained horizontal surface wave acceleration at a distance of 100 miles for a New Madrid fault zone earthquake should be 0.06 g.

Ground motion parameters necessary for dynamic testing are sustained horizontal acceleration, predominant period and duration of strong ground shaking. The sustained horizontal acceleration and predominant period have been estimated based on the currently available published literature. Dr. O.W. Nuttli has just completed a state-of-the-art paper which significantly modifies his previous estimates of ground motion parameters from central U.S. earthquakes. Nuttli's paper is the property of the U.S. Army Corps of Engineers and is presently being edited and is not available for use. Nuttli's paper should be available in the early part of November.

Stage III--Laboratory Activities

The principle activity in the laboratory has been the installation and modification of the dynamic loading system. The MTS closed loop dynamic loading frame required the installation of a hydraulic cooling system in the laboratory. In addition, modification of the load cell assembly were undertaken whereby a smaller (3000 lb), more sensitive load cell was substituted for the factory installed 20,000 lb load cell. This particular modification has just been completed and is currently undergoing testing.

Stage III--Mathematical Modeling

The mathematical analysis study has a goal of estimating the ground surface response of the microseismic zones when subjected to the anticipated rock accelerations. Although a variety of computer models are available, the program entitled SHAKE II was selected for use in the pilot study. Other codes such as FLUSH are more sophisiticated and perhaps better model the soil-rock environment than the SHAKE Code. However, due to the time constraints and the effort level that would be required to make FLUSH operational on UMC computing facilities and since SHAKE has been widely used for similar purpose by other agencies, it was selected for use.

PHASE II

The objectives of Phase II of the proposed research is to evaluate the level of severity of potential geological hazards associated with seismic activity. Zoning maps based on developed criteria will be prepared. In order to accomplish the goals of Phase II, the following principles and techniques are being utilized: Field Exploration and Laboratory Investigation, Analysis.

Stage I--Field Exploration

The field exploration phase has been completed as described previously. Further investigation may be required to refine the zone boundaries.

Stage II--Laboratory Investigation

This stage is currently under way as described previously. Completion is projected by January 1, 1979.

Stage III--Analysis

Currently, geologic microzones are being delineated for purposes of defining areas of similar geologic settings. These zones will then be modeled in the computer and their responses determined.

Analysis of Strong Motion Data and the Effects of Earthquake Source Parameters on Ground Motion in California

M. Nafi Toksöz and Anthony F. Shakal

Massachusetts Institute of Technology

1 January 1978 - 30 June 1978

The effect of the medium on recorded strong motion has been studied through the analysis of accelerograms and theoretical modelling. The variations of strong ground motion at nearby sites are strongly dependent on frequency. Comparisons of spectra and coherency between sites for the San Fernando and Kern County earthquakes show that the strong motion is coherent at low frequencies, but the coherency drops off at higher frequencies - between 1 and 10 hz, depending on station spacing and site characteristics. At high frequencies, the effects of attenuation and of scattering due to near surface heterogeneities and buildings are substantial.

The Pasadena and Lake Hughes area strong motion records from the San Fernando earthquake were re-examined to investigate the effects of local geology on the amplification of ground motion. Because of the frequency dependence of this amplification, it appears to be different when measured by a Wood-Anderson seismograph or by a strong motion acclerometer. At the low frequencies in the pass band of the Wood-Anderson, the strong motion shows effects of the sediment layering similar to those seen by Gutenberg. At the higher frequencies to which the acceleration is most sensitive, the shallow sedimentary layers have the greatest effect. Theoretical calculations made using different thicknesses of low velocity sedimentary layers show strong dependence of the amplitude of the recorded surface motion on the peak frequency of the incident pulse.

Instrument Development and Geotechnical Studies

8-9940-02089

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Investigations

1. Instrument Development - The objective is to develop a portable, low power consuming, micro-processor controlled, digital recording system to meet a wide range of field data recording needs. The key design goals include, software control, 16 bit resolution, modular design with an adaptable bus system to allow easy modification to adapt to changing recording objectives.

2. Geotechnical Studies
   a. In-situ geophysical measurements especially shear wave velocity and amplitudes.
   b. Controlled source seismic studies at critical sites.

Results

1. Instrument Development - The second round of the invitation for proposals yielded several technically acceptable proposals. After technical evaluation and cost analyses the contract was awarded to Argo Systems of Sunnyvale, CA. The first design meeting with representatives from UC Santa Barbara, Scripps, Cal. Tech, Argo, and USGS has been held. A prototype recording-playback system based on the UCSB ocean bottom system and compatible with the Cal. Tech. TIM system is scheduled for delivery in June of 1979.
2. Geotechnical Studies - Field tests of a signal enhancement recording system revealed some internal noise problems. The instrument has been returned to the factory for correction and for modifications to allow the integration of a visual monitor and a digital magnetic tape recorder into the system.

indicate large damage, and records obtained at long distances from large-magnitude earthquakes indicate less damage, even for the same observed peak amplitudes. Thus, statistical averaging over the entire data leads to the conclusion that estimating duration in addition to observing peak amplitudes will not lead to more refined damage estimates or design levels than using peak amplitudes alone. Of course this result depends on the simple description of input assumed here (magnitude, distance, and site conditions), and is valid only for the simple damage function used (hysteretic energy input to a bilinear structural model). Results for more elegant ground-motion models await the development of these models by geophysicists.

3. For calculating probabilities of liquefaction, use of the damage criterion proposed by Japanese colleagues leads to a simple scaling of probabilities for each magnitude and distance, and thus a scaling of the marginal probabilities. Including a function proposed by Seed for the "number of cycles" of motion versus magnitude does not radically alter the estimation of liquefaction as a function of magnitude and distance. However, this estimate does differ substantially from empirical observations of liquefaction (see attached figure), for reasons not yet well understood. Either observed liquefaction effects are not consistent at different magnitudes and distances or the mathematical models of shear stress traditionally used by soils engineers are inadequate. Further work is planned to resolve this problem.

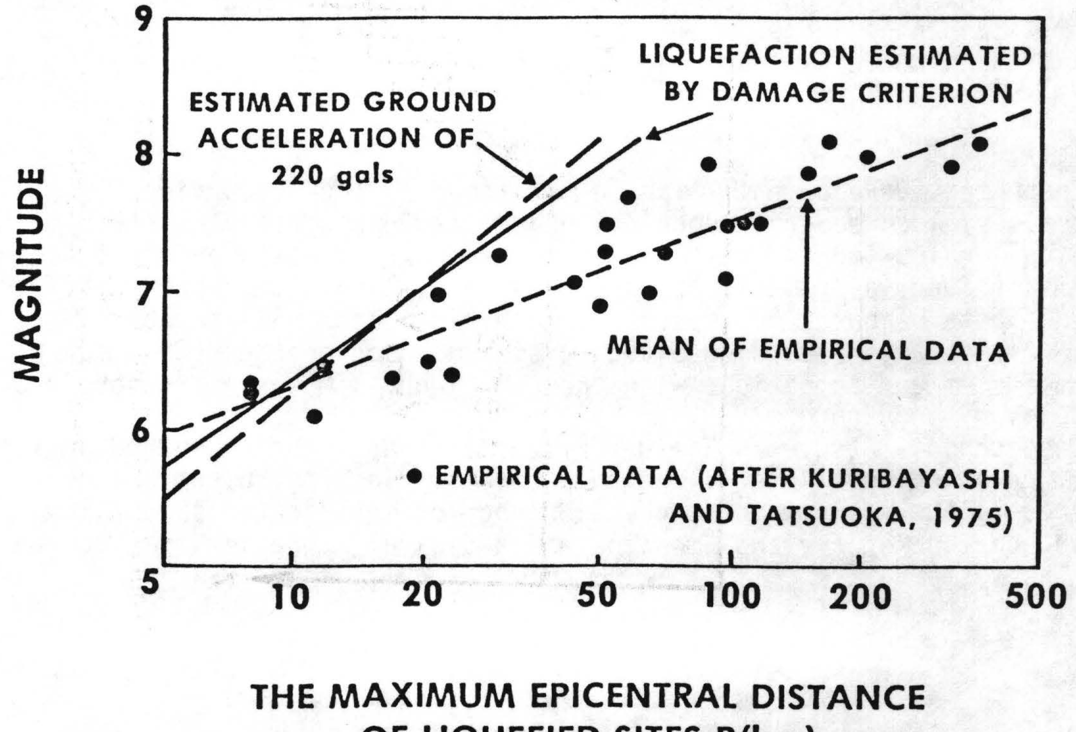

Figure 1.--Magnitudes and distances leading to liquefaction in 3-m deep layer, from empirical data and damage criterion. R, epicentral distance

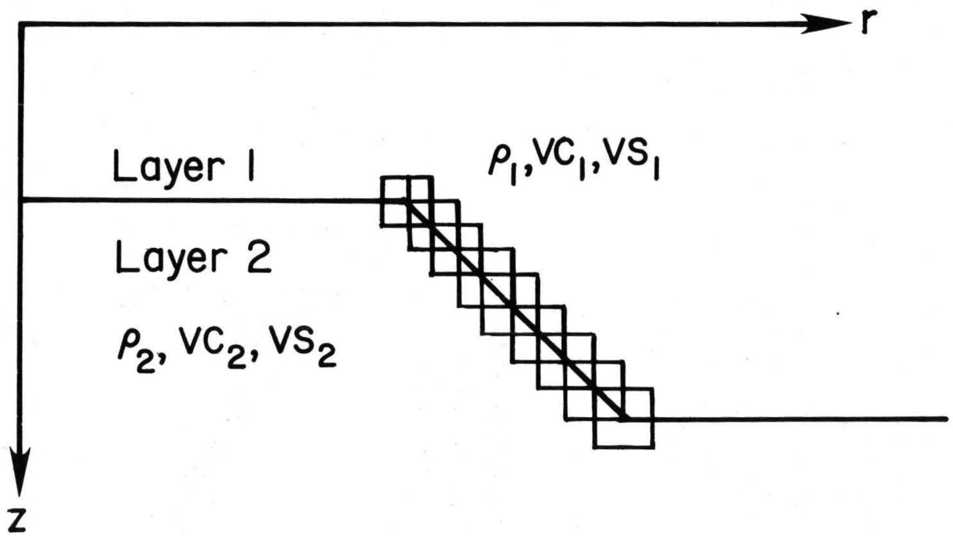

Figure 1.--Fitting finite elements next to a diagonal ramp. ρ_i, VC_i, VS_i = density, compressional speed, and shear speed, respectively; i = 1, 2.

DIFFRACTION OF WAVES BY THREE-DIMENSIONAL SURFACE TOPOGRAPHIES AND SUBSURFACE IRREGULARITIES

USGS Grant No. 14-08-0001-G-500

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Goal:

The objective of this research contract is to study the effects of irregular canyons and valleys on the amplitude of seismic waves. Since it is difficult to analyze exactly scattering surfaces of irregular shape, approximate methods based on Ohsaki's method are to be developed. This particular formulation can be made general so that the numerical algorithm may be applied easily for many irregular geometries and various boundary conditions.

Investigations and Results:

To evaluate the effectiveness of the Ohsaki's method in wave propagation, the numerical results have been compared with two existing exact solutions. The results compared favorably and the solution is shown to converge as the model is refined. Since the Ohsaki's method is based on superposition of fundamental solutions, a major effort of this research contract has been the numerical evaluation of the Green's function. Currently, computer programs have been created for two-dimensional Green's functions in an elastic half space and for point sources in a layered viscoelastic medium. Parametric studies are now planned for the analysis of wave scattering by canyons of arbitrary shape. Further development of this method will result in a hybrid finite element-continuum approach for problems involving localized inhomogeneities In this method, it is envisioned that the local analysis is best performed by a detailed finite element analysis while the wave transmission at the far field can be handled appropriately by Ohsaki's method.

APPENDIX A

SUMMARY OF RESEARCH CONDUCTED UNDER USGS CONTRACT #14-08-0001-G-500

Part I Development of Ohsaki's Method for Wave Propagation Problems

Since Ohsaki's method was developed to analyze static foundation problems in structural mechanics, the boundary conditions as well as the equation of motion have to be revised for wave propagation problems. To test the effectiveness of this method when applied to solve wave propagation problems, its solutions are compared to two exact solutions: (1) the scattering of a plane P-wave by a cylindrical void in an elastic full space, and (2) the scattering of a plane SH-wave by a semi-cylindrical canyon. Both of these solutions are expressed in infinite series of Bessel functions.

To construct an approximate solution for case 1 using Ohsaki's method, we must first locate observation points on the surface of the cylindrical void ($r=R_o$) as shown in Figure 1. Compressional and shear sources of unknown magnitude are then placed within the void boundary at $r = R_s$ to represent the outgoing scattered waves from the void boundary. The number of source points are made less than the number of observation points. Since the solution for a line source satisfies exactly the wave equation except at the source point, the superimposed solution outside the void boundary will thus satisfy the equation exactly everywhere. The approximation of this method, however, comes from matching the boundary conditions. Although it is unlikely that the boundary conditions can be matched perfectly by the assumed solution, the boundary conditions can be satisfied in the least square manner.

By taking a sufficient number of source points at appropriate locations, the boundary conditions can be matched well enough to produce excellent results. Shown in Table I are the comparisons for three different frequencies, $\eta = 0.5$, 1.0 and 2.0. The value of η is dimensionless and is normalized as $\eta = R_o/\lambda$; where λ is the wavelength of the incident wave. Thirty observation points are taken for all three cases, but the number of sources, N_s, has been varied for $\eta = 0.5$ to show the rate of convergence. Clearly, the result improves as N_s increases. For $\eta = 2.0$, more sources are needed to represent the high frequency scattering process, and the agreement is again excellent.

One of the difficulties that remains with Ohsaki's method is that it is an ad hoc approach in which the source location must be chosen arbitrarily. For high frequency scattering, the source points must be placed near the surface to produce a solution that varies rapidly over the boundary. But for low frequency cases, the sources must be pulled away from the boundary to produce a smooth influence from the sources. Figure 2 shows the magnitude of errors resulting from the least square boundary matching. There is a definite "optimal" location for the sources that yields the best solution, i.e., the least error on the boundary condition. Furthermore, the optimal location is dependent on the number of source points, N_s, and the error decreases as N_s increases. We are currently trying to develop a procedure in which this arbitrariness of source location can be eliminated

Part II <u>Development of Green's Functions</u>

For the scattering of in-plane waves in an elastic full space or anti-plane waves in an elastic half space, the Green's functions take the form of a Hankel function. Therefore, the numerical evaluation is quite straight forward and the effort is minimal. But for the case of an in-plane wave in an elastic half-space or a full three-dimensional problem in a layered medium, the Green's functions are in the form of an infinite integral with complex integrands, the numerical evaluation can be difficult and laborious.

In the first stage of our research, all the Green's functions have been derived and coded in FORTRAN. For the two-dimensional plane strain problems, the Green's functions are derived similar to the original derivation of the Lamb's problem except the observation point below the surface must also be accounted for. For the three-dimensional layered medium, the program developed by R. Apsel and J.E. Luco of the University of California at San Diego will be applied. Presently, the program is operating on our computing facilities, part of our future research shall be performed with collaboration from Professor Luco of the University of California at San Diego.

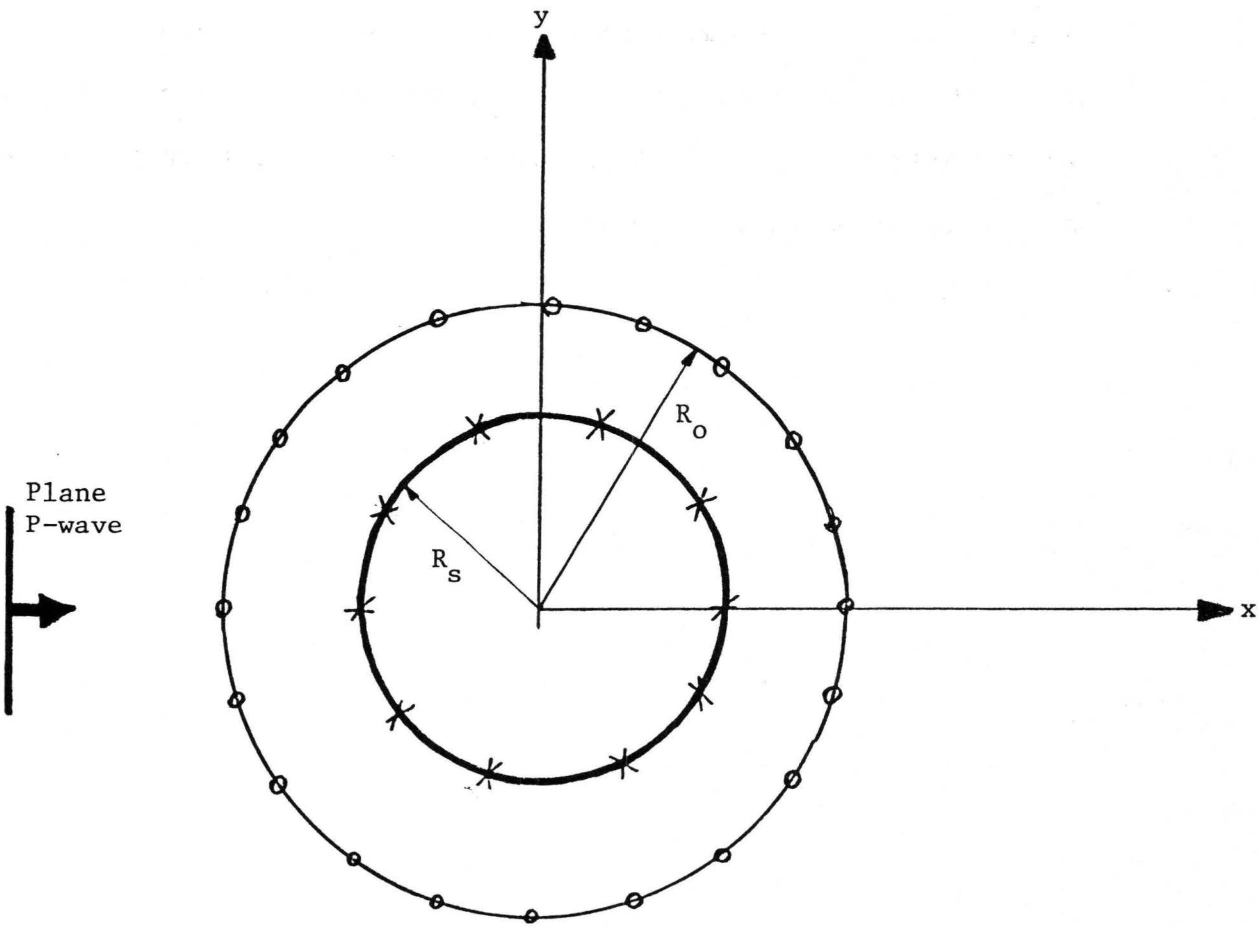

Figure 1

TABLE I

COMPARISON OF NUMERICAL VALUES $\eta = 0.50$ $N_o = 30$								
Θ	LS SOLUTION $N_s=8, \frac{R_s}{R_o}=0.09$		L SOLUTION $N_s=16, \frac{R_s}{R_o}=0.3$		LS SOLUTION $N_s=24, \frac{R_s}{R_o}=0.49$		EXACT SOLUTION	
0	(- 0.634	, 0.342)	(- 0.700	, 0.239)	(- 0.700	, 0.238)	(- 0.700	, 0.238)
$\pi/7$	(- 0.511	, 0.316)	(- 0.517	, 0.303)	(- 0.517	, 0.303)	(- 0.517	, 0.303)
$2\pi/7$	(- 0.305	, 0.248)	(- 0.234	, 0.335)	(- 0.235	, 0.334)	(- 0.235	, 0.334)
$3\pi/7$	(- 0.352	, 0.212)	(- 0.311	, 0.241)	(- 0.311	, 0.241)	(- 0.311	, 0.241)
$4\pi/7$	(- 0.717	, 0.390)	(- 0.766	, 0.343)	(- 0.766	, 0.344)	(- 0.766	, 0.344)
$5\pi/7$	(- 1.092	, 0.879)	(- 1.169	, 0.852)	(- 1.170	, 0.851)	(- 1.170	, 0.851)
$6\pi/7$	(- 1.288	, 0.417)	(- 1.284	, 1.463)	(- 1.284	, 1.463)	(- 1.284	, 1.463)
π	(- 1.345	, 1.638)	(- 1.274	, 1.727)	(- 1.273	, 1.729)	(- 1.274	, 1.729)

Θ	$\eta = 1.00$ $N_o = 30$				$\eta = 2.00$ $N_o = 30$			
	LS SOLUTION $N_s=16, \frac{R_s}{R_0}=0.35$		EXACT SOLUTION		LS SOLUTION $N_s=20, \frac{R_s}{R_o}=0.45$		EXACT SOLUTION	
0	(0.054	-0.405)	(0.056	, -0.401)	(-0.049	, 0.263)	(- 0.054	, 0.264)
$\pi/7$	(- 0.146	-0.276)	(- 0.144	, -0.281)	(0.129	, 0.014)	(0.133	, 0.011)
$2\pi/7$	(- 0.258	-0.003)	(- 0.261	, -0.001)	(0.048	, -0.354)	(0.046	, -0.353)
$3\pi/7$	(- 0.291	0.121)	(- 0.289	, 0.122)	(-0.359	, -0.145)	(- 0.360	, -0.144)
$4\pi/7$	(- 0.665	0.394)	(- 0.667	, 0.393)	(-0.534	, 0.567)	(- 0.534	, 0.566)
$5\pi/7$	(- 0.727	1.176)	(- 0.727	, 1.179)	(0.504	, 1.213)	(0.502	, 1.217)
$6\pi/7$	(- 0.248	1.873)	(- 0.246	, 1.870)	(1.756	, 0.540)	(1.759	, 0.538)
π	(- 0.045	2.081)	(0.043	, 2.083)	(2.030	, -0.004)	(2.028	, 0.001)

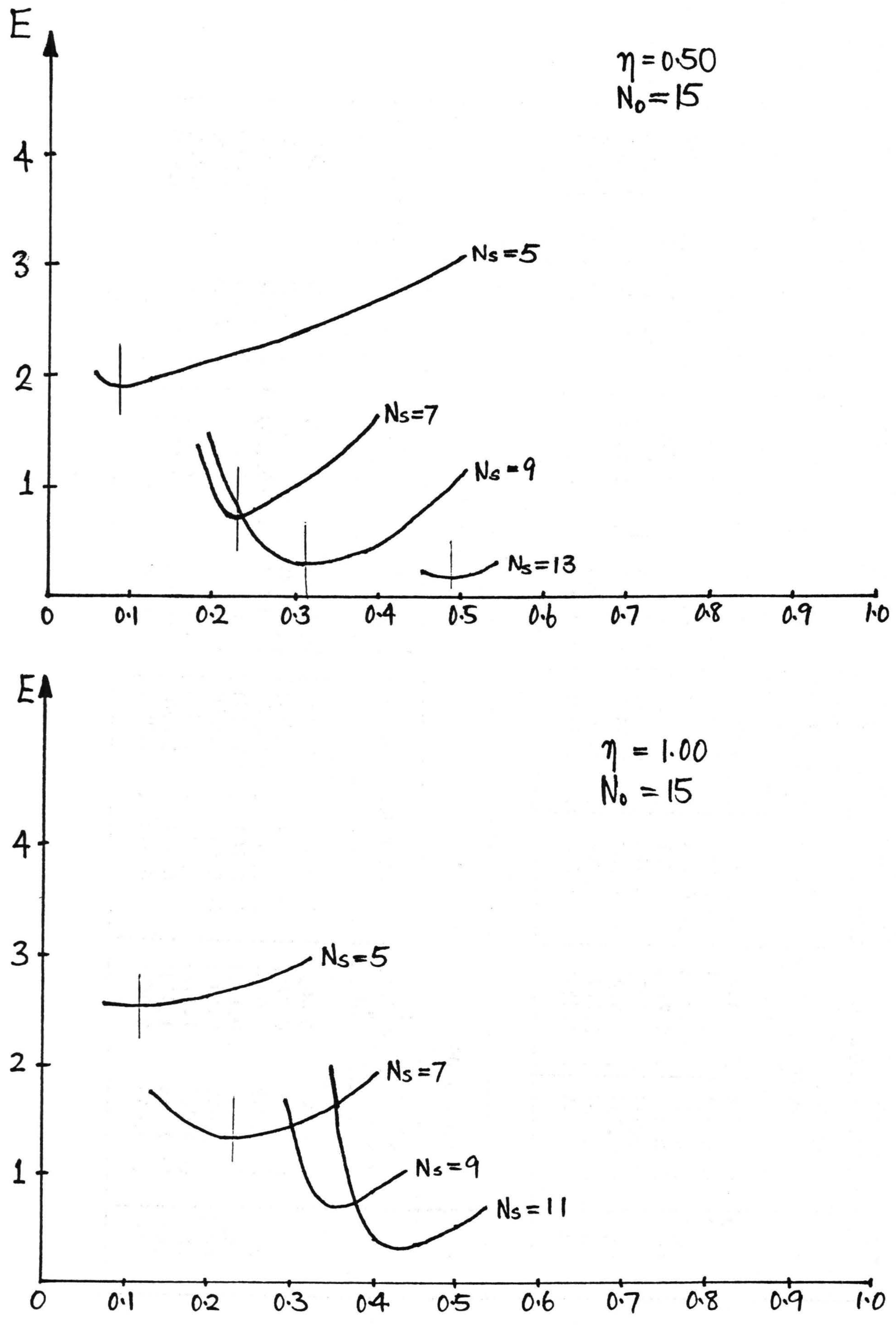
E
η = 0.50
N₀ = 15
Ns = 5
Ns = 7
Ns = 9
Ns = 13
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
E
η = 1.00
N₀ = 15
Ns = 5
Ns = 7
Ns = 9
Ns = 11
4
3
2
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 2

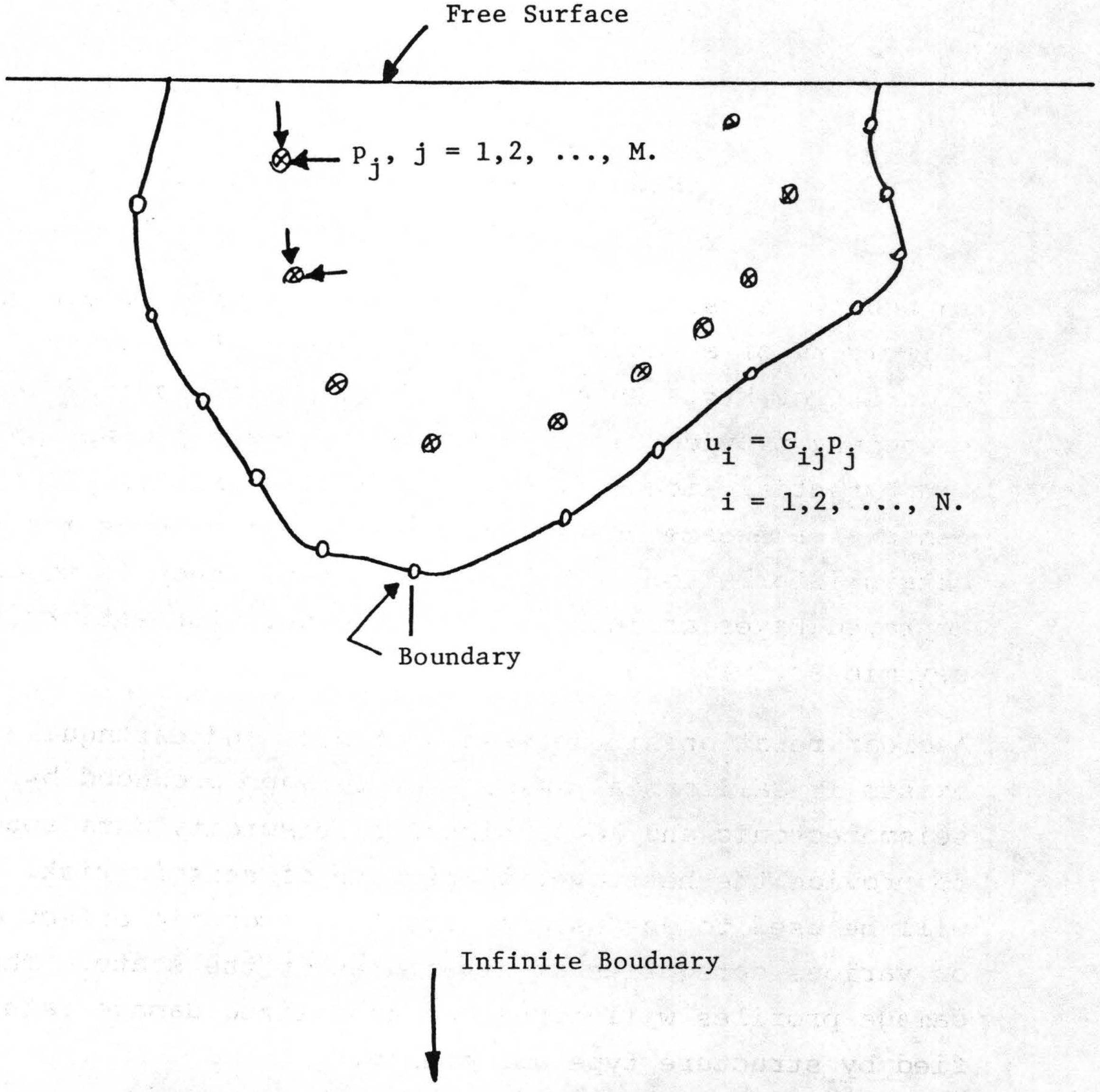
Free Surface
p_j, j = 1,2, ..., M.
$u_i = G_{ij}p_j$
i = 1,2, ..., N.
Boundary
Infinite Boudnary

Figure 3

Summary of Semi-Annual Technical Report

IMPROVED BAYESIAN SEISMIC INTENSITY MAPS OF CALIFORNIA WITH LOSS ESTIMATIONS

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In recent years, it has been common practice to evaluate the seismicity of a region by its frequency of occurrence of recorded events. However, it should be emphasized that this procedure provides a complete and adequate picture only when a substantial amount of historical data exists. In the absence of adequate historical data, other methods must be used to obtain information. The intent of this study is to develop an improved Bayesian seismic risk procedure for estimating future seismic activity in California.

A clear relationship between tectonics and earthquake occurrence exists in California. As a result, maps produced by combining seismotectonic and local historic seismicity data appear likely to provide the best overall picture of seismic risk. These maps will be used to assess the potential economic effect of earthquakes on various categories of structures in the state. The resulting damage profiles will appear as annualized damage rates, classified by structure type and county.

BAYESIAN ESTIMATION

The Bayesian procedure uses as a basis of comparison the amount of energy released per unit time or seismic energy flux ($\dot{E}$).

That is, prior estimates of the logarithm of the energy flux computed from geological information are updated by historical data. This procedure is illustrated below

$$\log E'' = \frac{\left(\dfrac{1}{\sigma^2_{\log \dot{E}'}}\right) \log \dot{E}' + \left(\dfrac{N}{\sigma^2_{\log \dot{E}}}\right) \log \dot{E}}{\left(\dfrac{1}{\sigma^2_{\log \dot{E}'}}\right) + \left(\dfrac{N}{\sigma^2_{\log \dot{E}}}\right)} \tag{1}$$

where the prime denotes the prior or geological estimate, the double prime donotes the posterior estimate, N denotes the number of observations and σ represents the standard deviation. The above formulation assumes that both $\dot{E}''$ and $\dot{E}'$ are lognormally distributed.

The historically-determined $\dot{E}$ is computed for an area or fault by summing the energy released by all recorded earthquakes and normalizing per recorded time period. The geologically determined $\dot{E}$ is computed from the following expression

$$\dot{E}' = S_R \eta \bar{\sigma} L_o W_o \tag{2}$$

where S_R is the average slip rate, η is the seismic efficiency, $\bar{\sigma}$ is the mean stress, W_o is the width of the fault and L_o is the length of the fault. The product of η and $\bar{\sigma}$ is also referred to as the apparent stress. The parameters of Equation 2 are being determined for faults in California, Nevada, Arizona, and Northern Mexico by conducting a survey of geologists and seismologists. Each is being asked to indicate his judgement on such subjects as fault delineation, relative activity, fault type, maximum magnitudes, slip rate, apparent stress and fault dimensions. Preliminary results indicate, for example, that the range of slip rates for the San Andreas fault are believed to vary from 1 to 5 cm/yr; the larger values apply to the northern part of California.

ATTENUATION

Numerous relationships for the attenuation of ground motion with distance have been developed for the western United States. In general, these relationships are derived from the same data base. However, when expected ground motions are computed using these relationships, the variation in the results is quite large. These large differences are presumably caused by differences in data interpretation or in the procedure used to develop the relationship.

To incorporate the variation in these attenuation equations, a procedure has been developed whereby "average" relationships for each mode of ground motion (e.g., peak acceleration, peak velocity and peak displacement) are derived from a weighted average of all available relationships. This analysis should be distinguished from one which uses actual earthquake data as a data base. The weighting factors for each equation are determined by how well the equation fits existing data (i.e., correlation coefficient) in selected magnitude and distance ranges.

The data base will include all Cal Tech free field, ground level, and basement records. Selected USGS integrated records for the western hemisphere will be used to supplement this data base.

DAMAGE AND EXPOSURE MODELS

The principal work remaining consists of developing the damage and exposure models for California. These models will be used to compute damage profiles for various categories of structures in California.

A STUDY OF THE BEHAVIOR OF CEMENTED SOILS UNDER SEISMIC LOADING

G.W. Clough
Stanford University

In March of 1978, the U.S.G.S. funded a one year study on the behavior of cemented soils under seismic loading with Stanford University. Professor G.W. Clough of the Civil Engineering Department is the principal investigator. This report is submitted to summarize the progress in the first six months of the research.

The term "cemented soil" is meant to include a category of sandy and silty materials which exhibit an unconfined compressive strength which is typically 690 kN/m^2 (100 psi) or less. After failure in unconfined compression, cemented soils exhibit little, if any, residual strength. These materials are of particular interest in regard to their behavior in seismic events since cementation can help the soil resist seismic loads, but at loads beyond failure, a significant reduction in strength occurs. Natural slopes in cemented soils are often very steep and can reach surprising heights in even weak members of this family. Upon failure of such slopes, catastrophic results occur, since near the unconfined slope face, the soils suddenly have sandy soil to resist liquefaction. A small degree of cementation is known to substantially reduce the susceptibility of a sand to initial liquefaction (4, 8). However, if the cementation effects are overcome, a sudden failure can result.

Cemented soil deposits are common to many areas in the world, including the U.S. The most recent spectacular example of their behavior in an earthquake occurred in 1976 in Guatemala. In this country, wind-blown pumice deposits are present in abundance near the large urban centers. The pumice stands in 30 m (100 ft) high vertical slopes, yet it can be easily scraped away by a light pressure. Thousands of landslides occurred in the pumice in the 1976 earthquake, collapsing beneath homes and onto highways.

In the San Francisco Bay Area, cemented soils exist in abundance in the hills in the South Bay region, in the Santa Cruz Mountains, and along the Pacific Coast from Half Moon Bay to San Francisco. In the 1906 earthquake considerable numbers of slope failures occurred in the cemented soil deposits (4, 11). Dramatic examples occurred along the coast just north of Mussel Rock and in the Santa Cruz Mountains. The scars from these landslides are readily evident today. Again in the 1957 Daly City earthquake, numerous landslides occurred in the area north of Mussel Rock; this led to the abandonment of the old route for Highway One and a railroad alignment.

The available field evidence suggests that a study of cemented soils is of interest to earthquake hazard reduction in the Bay Area as well as in many other areas. Interestingly, little work has been done on these materials, perhaps because they are very difficult to sample and the importance of cementation is only now being recognized. In the original proposal for the present effort, a program of research was described which could address the entire scope of problems associated with cemented soils. The long-range objectives were as follows:

1.) Establish acceptable means of sampling and testing of cemented soils;
2.) Define the failure and stress-strain response of a range of cemented soils under static and dynamic loadings;
3.) Develop a procedure for analysis of cemented soil slopes subjected to seismic loadings;
4.) Define the liquefaction potential of naturally occurring cemented soils.

Of course, a research program with such a large scope of objectives can only be accomplished over a period of a number of years. For the one year contract of the present research, it was proposed to concentrate on the first two long-range objectives and begin work on the third as the information from the first two was developed. Completion of the third objective will require that a second year effort be funded. Work towards the fourth objective could begin in the second year but would require additional time.

Considerable progress towards the immediate research goals has been made in the first six months and it is expected that all objectives originally envisioned for the first year will be achieved by the end of the present contract period (scheduled for March of 1979). Results from the first six months efforts are described subsequently in this report.

A STUDY OF THE SUSCEPTIBILITY TO LIQUEFACTION OF THE SAN FRANCISCO WATERFRONT FILLS

G.W. Clough, Principal Investigator
Stanford University

INTRODUCTION

In January of 1978, a study was begun at Stanford University to investigate the susceptibility to liquefaction of man-made fills placed prior to 1906 during the construction of the San Francisco Waterfront. The motivation for the work was provided by the fact that several areas of these fills liquefied in the 1906 San Francisco earthquake, but no detailed study has been made of the reasons for the failures. Also, at the present time, the City of San Francisco is constructing a network of sewers through the waterfront area, the excavations of which will expose the fill soils, allowing visual inspection and ready opportunity for sampling.

The plan view of the San Francisco Waterfront given in Figure 1 illustrat the area of general interest. The study is concentrating on the main waterfront thoroughfare, the Embarcadero, between Berry Street on the southern end and Northpoint Street on the northern end. Basic tasks undertaken in the research include the following:

1. Documentation of historical information on waterfront fill construction and available boring data from recent exploration work for the new sewer system.
2. Performance of field and laboratory tests to define the character of the fill materials.
3. Monitoring of the effects of pile driving on the fill soils during sewer construction.
4. Performance of analytical studies to define acceleration levels which might be expected along the waterfront during seismic events.
5. Explain the reasons for the behavior of the fill soils during the 1906 earthquake.
6. Evaluate the potential for liquefaction in future seismic events.

The remainder of this report gives a summary of the progress towards the goals of the research during the first six months of work.

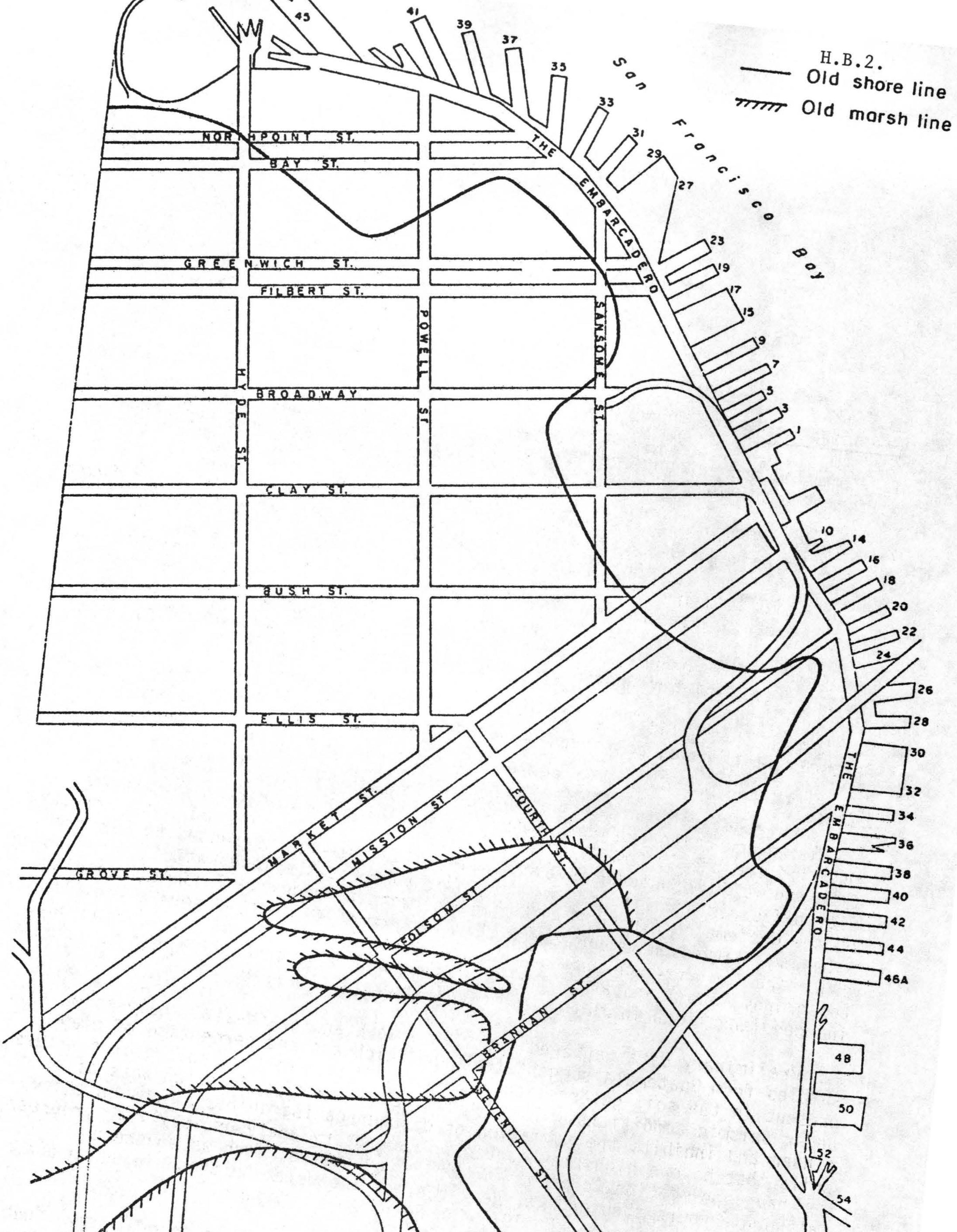

FIGURE 1. WATERFRONT AREA OF SAN FRANCISCO SHOWING OLD SHORELINE.

Earthquake-induced landslides

8-9550-01452

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Investigations

1. Compiled and categorized the detailed seismic-induced landslide distribution from the 1976 earthquake in the Gautemala City area.

2. Conducted field and laboratory research on mechanisms of seismic-induced debris slides and rockfalls.

3. Conducted research on delayed effect of earthquake-induced landslides on the static slope failure process in Guatemala.

4. Investigated ground-failure effects from the M=7.5 June 12, 1978, Off-Miyagi Prefecture earthquake near Sendai, Japan.

5. Investigated landslide incidence from the M=5.1 August 13, 1978, Santa Barbara, California, earthquake.

Results

1. A map depicting the concentration of landslides on canyon slopes was compiled for the Guatemala City area (see fig. 1) using mapped landslide data from the 1976 earthquake investigation. This map was presented to Guatemala City officials and citizens as part of a paper at the International Conference on the Guatemalan Earthquake and Reconstruction Process. Further investigation and analyses have indicated that the zones of high and severe landslide concentration shown on this map reflect physical site conditions (lithology, topography, etc.) and are, therefore, areas of high susceptibility to seismic-induced landslides in future earthquakes.

2. Preliminary data gathered from field work and grain-size analysis of soil samples from Guatemala suggest that the thickness and percentage of clay present in the soil governs its susceptibility to forming soil debris slides under seismic conditions. It is likely that the clay fraction acts as a binder and inhibits the formation of disaggregating debris slides in thick soils that have a high clay content. Laboratory analyses, still in progress, may have application to areas in the United States, such as southern California where thousands of debris slides, similar to those in Guatemala, occurred in response to the 1971 San Fernando earthquake.

3. Correlations of rockfall occurrence with lithology in several major and moderate earthquakes have indicated that, for most well-cemented rocks, the fracture or joint spacing, orientation, and proximity to steep slopes greater

than 35° are the most important parameters determining the susceptibility of a rock mass to seismic-induced rockfalls. For weakly-cemented rocks, fractures and joint spacing are not as important in controlling their seismic deformation. The cohesion of many such rocks is low enough that seismic shaking produces additional fractures through previously intact rock. Although most weakly-cemented materials tend not to form steep natural slopes, materials such as volcanic pumice tuffs commonly form nearly vertical slopes several hundred meters in height although essentially uncemented. These materials have a high internal friction, a result of the shape and interlocking nature of individual particles, and are thus stable under static conditions. However, the low tensile strength of these rocks is apparently responsible for their extreme seismic instability, as evidenced by the extensive rockfall occurrence in such deposits in Guatemala. Such weakly-cemented materials are highly susceptible to the generation of seismic-induced rockfalls whether containing extensive or few fractures.

4. Reinspection of landslide-affected slopes from the 1976 Guatemala earthquake in May 1978 revealed that the largest landslides created in the earthquake showed no evidence of renewed movement despite the effects of two annual rainy seasons since the earthquake. Several large incipient landslides were also inspected, and the same conclusion reached. Extensive rainfall-induced reactivation, however, was observed on slopes where small (<15,000 m^3 volume) though numerous rockfalls and debris slides occurred in 1976. The 1976 earthquake, therefore, has resulted in accelerated mass wasting where smaller falls and slides occurred and will probably continue to occur with gradually diminishing effect over many years.

5. Reconnaissance of ground failure in Miyagi Prefecture, Japan, established that several thousand landslides were triggered in response to the magnitude 7.5 earthquake. Most were small rockfalls and rockslides originating in steep roadcuts and natural slopes of Mesozoic metamorphic rocks and Miocene volcanic deposits. The largest rockfalls (several thousand m^3 volume) were in Miocene tuff breccia. The largest of these damaged 4 houses located at the base of the failed slope. Several houses and roads were also affected by rotational slumps and settlement in loosely compacted artificial fills. A housing development in Sendai experienced the largest of these, about 30,000 m^3 volume. In all, seismic-induced landslides accounted for two houses destroyed and 13 damaged. The main factors governing landslide occurrence appeared to be the presence of weakly-cemented and/or extensively jointed rocks exposed in steep slopes in the cases of rockfalls and loosely compacted artificial fill in the cases of the rotational slumps.

6. Landslides from the M=5.1 August 13, 1978, Santa Barbara earthquake were mainly small rockfalls and rockslides from steep roadcuts. One large (100 m^3) rockfall in conglomerates of the Tertiary Sespe Formation closed California Highway 154 near San Marcos Pass in the Santa Ynez Range for 30 hours. Weakly-cemented and heavily fractured sandstones in the Tertiary Coldwater Formation also produced rockfalls and slides in the Santa Ynez Range. Other small rockfalls occurred along the coastal cliffs near Santa Barbara in the Tertiary Monterey and Sisquoc shales. Seismic-induced settlement of a railroad embankment west of Santa Barbara near Ellwood was responsible for a train derailment occurring 7 minutes after the earthquake. Our conclusions were that the landslide occurrence from this moderate earthquake indicated that steep slopes in weakly cemented and extensively fractured rocks were the most

susceptible to seismic-induced failure. Most of the steep slopes in these rocks are roadcuts, and the same areas will likely sustain failures in future earthquakes of magnitude 5 or greater in the Santa Barbara channel area.

Reports

Harp, E. L., Wieczorek, G. F., and Wilson, R. C., 1978, Earthquake-induced landslides from the February 4, 1976, Guatemala earthquake and their implications for landslide hazard reduction: International Symposium on the February 4, 1976, Guatemalan Earthquake and the Reconstruction Process, Guatemala City, Proceedings.

Harp, E. L., Wilson, R. C., Wieczorek, G. F., and Keefer, D. K., 1978, Landslides from the February 4, 1976, Guatemala earthquake--Implications for seismic hazard reduction in the Guatemala City area: 2nd International Conference on Microzonation, San Francisco, Proceedings.

Keefer, D. K., Wieczorek, G. F., Harp, E. L., and Tuel, D. H., 1978, Preliminary assessment of seismically induced landslide susceptibility: 2nd International Conference on Microzonation, San Francisco, Proceedings.

Harp, E. L., 1978, Landslides resulting from the June 12, 1978, Off-Miyagi Prefecture earthquake: Earthquake Eng. Res. Inst. Bull. (in press)

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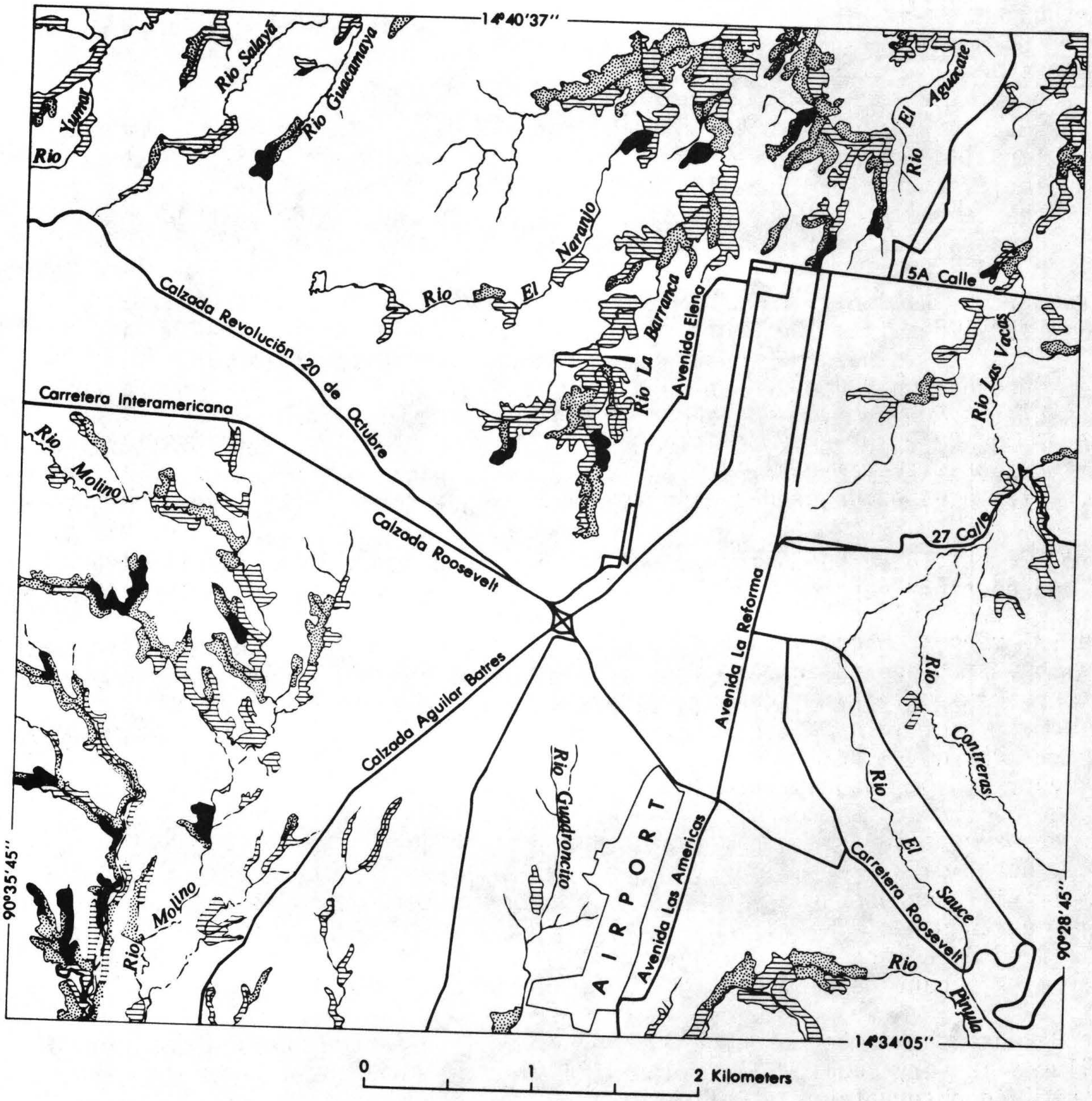

EXPLANATION

Landslide concentration (in percent)

0-5 Low	5-20 Moderate	20-50 High	>50 Severe

Ground Failures Caused by Historic Earthquakes

8-9550-02161

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Investigations

1. Deborah Tuel and I continued to assemble and abstract reports on major historic earthquakes. From these reports, we are extracting data on the extent and types of ground failures (slope failures, fissuring, settlements, bearing capacity failures, etc.) and on the geologic environments in which these failures occur, and a major product of our research will be a synthesis of this information. The quality of data concerning ground failures can be divided into three categories: (1) high quality reports focused specifically on ground failures, (2) moderate quality reports where ground failure information is available but is diffuse and can be extracted only with some effort, and (3) reports where ground failures are mentioned but where information on geologic setting and failure type can only be extracted with a large amount of effort by tracking down general geologic reports on the area, unpublished information or information sorted in archives. We are currently concentrating our efforts on reports in the second category, since information in the first category can be incorporated into the final synthesis with relative ease. It is not our intention to review reports from every major historic earthquake; rather we hope to assemble data from a sampling of events large enough so that the general data trends concerning ground failures are reasonably clear. This sample will include several small to moderate-sized events as well as many major earthquakes. Detailed studies of individual earthquakes for which the published data base is poor (Category 3) may also be pursued if it is judged that significant new information can be obtained.

2. Because the number of high quality reports on earthquake-induced ground failures is very small, I am continuing to supplement the literature search with field observations. Following a M=7.4 earthquake that occurred near Sendai, Japan, on June 12, 1978, I spent two weeks in Sendai and Tokyo with E. L. Harp and C. M. Wentworth observing ground failure effects and making contact with Japanese scientists and engineers engaged in comprehensive studies of the earthquake. During this trip, I also visited the Izu Peninsula, where an earthquake in January 1978 triggered numerous destructive landslides. Following the M=5.1 Santa Barbara, California, earthquake of August 13, 1978, I participated in a field reconnaissance study with E. L. Harp and R. C. Wilson of landslide effects.

Results

1. Preliminary analysis of slope failures in 15 historic earthquakes has been completed (Table 1, from Keefer, Wieczorek, Harp, and Tuel, 1978). The number

of slope failures triggered by an earthquake was found to be strongly dependent on earthquake magnitude. The predominant types of slope failures were falls and shallow slides in rock; avalanches, falls, and shallow slides in soil; lateral spreads; cut-slope failures; and slumps and block slides in rock and soil. Other types of slope failures occur less frequently during earthquakes but have high inherent potentials for causing loss of life and property. These include rock avalanches, lateral spreads, wet flows, subaqueous landslides, and liquefaction-induced failures in artificial fills. Some geologic environments with high susceptibilities to earthquake-induced slope failure were also identified on a preliminary basis.

2. The Off-Miyagi Prefecture, Japan, earthquake of June 12, 1978, caused liquefaction at several sites on the coastal plain in the Sendai area and numerous slope failures in hilly and mountainous terrain. Liquefaction occurred in Holocene coastal flood plain deposits consisting mainly of sand and silt and in uncompacted, hydraulic fills consisting of fine sand. The liquefaction damaged flood control dikes along several major rivers and port facilities in the town of Ishinomaki. The most abundant slope failures were small rockfalls and rockslides on steep slopes. There were also a surprisingly large number of slumps and debris slides in artificial fills, and these caused significant damage.

3. The August 13, 1978, Santa Barbara earthquake (M=5.1) triggered small rockfalls and rockslides on cut-slopes and coastal cliffs. The largest slope failure noted was a rockfall in a roadcut that involved about 100 m^3 of debris. This rockfall blocked a major highway for about 30 hours. A train derailment was probably caused by vibrational compaction in fill. From the small size and limited distribution of the ground failures in this earthquake, it appears that it is near the lower-bound event for which significant ground failure effects in this area could be expected.

Reports

Harp, E. L., Wilson, R. C., Wieczorek, G. F., and Keefer, D. K., 1978, Landslides from the February 4, 1976, Guatemala earthquake--implications for seismic hazard reduction in the Guatemala City area. International Conference on Microzonation for Safer Construction Research and Application, 2d, San Francisco, Calif., Nov. 26-29, 1978, 12 p. (in press)

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Keefer, D. K., and Johnson, A. M., 1978, Mobilization and movement mechanics of earthflows: Symposium on the Mechanics of Landslides and Slope Stability, Gainesville, Fla., Dec. 4-6, 1978, American Society of Mechanics and Society of Engineering Scientists, 4 p. (in press).

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Youd, T. L., and Keefer, D. K., 1978, Liquefaction and landslides in the November 23, 1977, earthquake in San Juan, Argentina [abs.]: Geological Society of America Abstracts with Programs, Ann. Mtg., Toronto, v. 10, no. 3, p. 521.

TABLE 1: LANDSLIDES TRIGGERED BY EARTHQUAKES

LANDSLIDE TYPE[I]	EARTHQUAKE NAME, DATE, AND MAGNITUDE: Kansu, China 1920 M 8.6	Alaska 1964 M 8.4	Chile 1960 M 8.4	San Francisco, Calif. 1906 M 8.3	Hawke's Bay, New Zealand 1931 M 7.9	Peru 1970 M 7.7	New Madrid, Mo. 1811 MMI XII	Guatemala 1976 M 7.5	San Juan, Argentina 1977 M 7.4	Hebgen Lake, Mont. 1959 M 7.1	Inangahua, New Zealand 1968 M 7.0	San Fernando, Calif. 1971 M 6.4	Borrego Mountain, Calif. 1968 M 6.4	Managua, Nicaragua 1972 M 6.2	Fortuna-Rio Dell, Calif. 1975 M 5.7
A. LANDSLIDES IN ROCK															
ROCK FALL - AVALANCHES		E	S	M		S				S	S				
SLUMPS AND BLOCK SLIDES			M	E	M	S		S			S	M	S		
FALLS AND SHALLOW, DISINTEGRATING SLIDES		E	M	E	M	E		E	M	E	M	M	S	S	S
B. LANDSLIDES IN UNCONSOLIDATED OR POORLY CONSOLIDATED DEPOSITS (ENGINEERING SOILS)															
FALLS, AVALANCHES, AND SHALLOW, DISINTEGRATING SLIDES	E	M	M	E		E	E	E			S	M	S	S	S
SLUMPS AND BLOCK SLIDES		E	M	E	S	M				S	S	S	S	S	
RE-ACTIVATION OF DORMANT LANDSLIDES		S	S	M		S				S	S	S			
LATERAL SPREADS[II]		E	M	E	M	S	E	S	E			S			
WET FLOWS[II]		E	M	M		S				S	S				
SUB-AQUEOUS LANDSLIDES[II]		E	S					S		S					
C. LANDSLIDES INVOLVING ARTIFICIAL CUTS OR FILLS															
CUT-SLOPE FAILURES		M	M	M	M	M		M	S	S		S	S	S	
LIQUEFACTION-INDUCED LANDSLIDES IN ARTIFICIAL FILLS		S	S	M	S	S					S	S			
LANDSLIDES IN ARTIFICIAL FILLS NOT CAUSED BY LIQUEFACTION			S	S	S	S						S	S	S	

[I] Classifications after Varnes (33).

[II] Liquefaction may be primary or contributing cause of failure.

[III] Small landslides are those judged to contain less than 10,000 m^3 of material.

[IV] Large landslides are those judged to contain more than 10,000 m^3 of material.

Explanation

E - Large number of landslides
> 5,000 small[III] landslides, or
> 100 large[IV] landslides, or
Landslides common over >1000 km^2 area

M - Moderate number of landslides
500 to 5000 small[III] landslides, or
10 to 100 large[IV] landslides, or
Landslides common over 100 to 1000 km^2 area

S - Small number of landslides
< 500 small[III] landslides, or
< 10 large[IV] landslides, or
Landslides common over <100 km^2 area

No symbol - No landslides of this type reported

References:

Kansu, China: 5, 15
Alaska: 19, 31
Chile: 6, 26
San Francisco: 36
Hawke's Bay: 20
Peru: 2, 8, 28
New Madrid: 10
Guatemala: 11, 12
San Juan, Argentina: T. L. Youd, D. K. Keefer, and others, unpub. data
Hebgen Lake: 1, 4, 9, 25, 29, 30
Inangahua: 21, 22, 23, 27
San Fernando: 14, 16, 17, 35
Borrego Mountain: 3
Managua: 7
Fortuna-Rio Dell: 18

Technical Report Summary USGS Contract #14-08-0001-16810

SURFICIAL LANDSLIDES TRIGGERED BY SEISMIC SHAKING, SAN FERNANDO EARTHQUAKE OF 1971

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In the 1971 San Fernando Earthquake, more than 1000 small shallow ground failures occurred in the hills north of San Fernando. These ground failures were not very damaging because they were largely confined to unpopulated National Forest lands. However, shallow landslides associated with large earthquakes have been very destructive in the past, and they present a growing hazard to life and property as metropolitan areas seek to expand into the adjacent hillsides and mountain valleys.

This project is an attempt to define the geological parameters that controlled the stability of slopes near San Fernando subjected to the 1971 earthquake. Since the slides differ in geometry and failure mechanism from slow rotational or coherent translational slides, the model of the slide and the resulting engineering analysis of its stability is quite different. During an earthquake, parts of a slope may fail despite the fact that on a gross scale, the slope is stable.

To date we have completed two basic studies of the earthquake-induced slides. First we examined gross lithology, slope angle and slope direction for a set of 250 randomly chosen slides. Second, we chose approximately 60 slides for field analysis and completed our field investigation of their geologic settings. Approximately 30 of these slides are still well enough preserved to warrant more detailed sampling and subsurface investigation. These slides share many common characteristics and will serve as the basis for development of engineering models. Even before completion of the engineering phase, we have developed a number of preliminary conclusions of interest:

1. There appear to be two distinct types of slides that were common in the San Fernando Earthquake. The first involved a thin layer of clayey to silty soil or colluvium which slid on slopes of 1:1 to 1.5:1. These were true soil failures and they have been analyzed in some detail by Bing Yen in another study within the Program. The second type was a rock fall or rock topple in which bedrock

separated from a relatively steep cliff and fell, slid, or rolled to rest downslope. The rock materials were commonly conglomerates, coarse sandstones, and blocky jointed gneisses and granite. Our study has concentrated on this second type of failure.

2. Rock falls were strongly influenced by topographic and geologic setting. While bedding orientation was relatively unimportant, joint sets and occasionally foliation in the basement complex were used as both the breakaway surface and the slide surface where sliding did occur. A steep topographic face was common to most falls. The topography after failure was very similar to the topography before failure, except that the scarp had migrated upslope.

3. Heavy rainfall just before an earthquake is not expected to increase the severity of the rock falls since open joints are already abundant in the ground and water can freely escape from the area. In contrast, the shallow soil failures may be greatly increased by rainfall since the soil properties are so strongly affected by moisture.

4. Areas of high rock fall hazard should be detectable well in advance of an earthquake. From our evidence to date, a combination of lithology, local steep relief, and jointing or foliation appear to be required for these failures to occur. The hazard can be quite severe, as illustrated by the relatively heavy damage in Pacoima Canyon from larger versions of the same surficial failure mechanism.

Analytical techniques for determining slope stability for these slopes under earthquake loading conditions remain to be refined, and this is the thrust of the remaining portion of the contract. Our work to date has been encouraging: the failures do share common geotechnical parameters, and they appear to be well suited for pre-earthquake detection and hazard evaluation. The application of this type of analysis should find very general use in areas of steep cliff topography in earthquake zones.

Ground Failure Related to the New Madrid Earthquake

8-9550-02160

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Investigations

1. Collected field engineering data from State and Federal agencies to determine engineering properties of sands, thickness of fine-grained topstratum, and location of ground-water table. Have contract with Corps of Engineers, Memphis District, to determine field engineering data at localities where existing data are inadequate.

2. Collected historic information that might be of value in interpretation of distribution of sand blows, such as oldest available airphotos, soil maps, and ground-water data.

3. Made field examinations of suspected sand blows, to determine if they were blows, mima mounds, or sand dunes.

Results

1. Field observations north of New Madrid, to Charleston, Missouri, tend to confirm the contention by Saucier ("Effects of the New Madrid Earthquake Series in the Mississippi Alluvial Valley" Miscellaneous Paper S-77-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., February 1977) that sand boils extend much further north of New Madrid than was known previously. Laboratory tests are being conducted on samples recently collected in the field to make certain the sandy deposits at the surface, which have the appearance of sand boils, are not dune sands.

2. SPT (Standard Penetration Test) data throughout much of the area between Marked Tree and New Madrid commonly have a characteristic pattern based on examination of data collected from the Corps of Engineers. Low blow counts in sands are commonly encountered from the base of a clayey stratum at the surface to a depth of about 30 feet, where the counts become significantly higher. These high blow counts usually extend to depths of 60 to 80 feet (the bottom of the hole). The sands with the low blow counts would almost certainly liquefy during an Intensity 7 earthquake; most sands with the higher counts would not liquefy. It is not known if this break in blow counts represents differences in characteristics of previously liquefied and non-liquefied sands, or is the result of a geologic mechanism such as reworking of sands associated with deposition of the clayey stratum. SPT data collected thus far south of Market Tree and north of New Madrid are very sparse, not permitting comparison with the region between Marked Tree and New Madrid.

3. Sufficient data have been collected and plotted to show there are regional, systematic patterns in the thickness of topstratum (fine grained,

capping stratum) across the Mississippi Alluvial Valley (east-west), from Marked Tree to New Madrid. In general, the most intense sand blow development (based on airphotos from 1930's and 1940's, and from Soil Survey maps made from 1912-1918) closely reflects where there is a thin (<10 ft) thickness of topstratum, with some major exceptions. Reasons for these exceptions are not yet known, but may include intensity of ground shaking.

Reports

None.

Interactions Between Ground Motion and Ground Failure

8-9550-01628

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Investigations

1. Continued development of MULTICS software for numerical simulation of the dynamics of earthquake-induced landslides.

2. Participated in a field reconnaissance of ground failures from the Santa Barbara Earthquake of August 13, 1978.

Results

1. The project continued to develop programs for numerical simulation of the dynamics of seismic-induced landslides, with the objective of developing a relatively simple, practical technique for evaluating slope stability under seismic ground motion conditions. A set of programs was written which uses the method of Newmark (1965) to estimate the displacement of a "block glide" landslide during a given design earthquake. The Newmark method models the landslide mass as a rigid friction-block with a "critical acceleration" (frictional-resistance/mass) derived from the slope and the "factor of safety," which is calculated, in turn, from standard slope stability analysis. The displacement of the block is then calculated from the acceleration time-history of the design earthquake--possibly a strong-motion record of an actual earthquake. Of course, this displacement is the lower-bound of possible displacements, since in an actual case, the landslide could lose enough strength to continue downslope under its own weight after the earthquake is over. However, the "Newmark displacement" still provides a good relative measure of seismic slope stability.

The seismic slope stability programs developed by this project embody a number of improvements on the original Newmark method. The most significant improvement is the direct simulation of the movements of the friction-block using the complete hysteresis loop, rather than the "mirror image" double-integration technique of Goodman and Seed (1966) which introduces an undesirable work-hardening characteristic to the friction-block. The improved Newmark method programs are significantly more realistic than the pseudo-static analysis currently used to estimate seismic slope stability, yet are far less complex and expensive than dynamic finite-element methods.

Graphs of landslide displacement versus critical acceleration for several historic strong motion records are presented in figure 1 as an example of the use of the improved Newmark method software. Note the strong dependence of the predicted landslide displacement on the critical acceleration of the landslide and (b) the severity of the seismic ground motion. For example, a landslide with a critical acceleration of 1 percent of the acceleration of gravity (g) would be displaced almost 200 cm for the El Centro 1940 (N-S) record, but another landslide with a critical acceleration of 10% of g would move less than 10 cm for the same record. On the other hand, a landslide with a critical acceleration of 10% g would be displaced over 100 cm by the Pacoima record, but less than 0.2 cm by the Taft record. Therefore, the improved Newmark method not only provides a measure of relative seismic slope stability (displacement for a given critical acceleration versus different earthquake records), but as suggested by figure 1, the improved Newmark method software may eventually even provide an instrumental scale for seismic intensity.

2. R. Wilson, E. Harp, and D. Keefer performed a reconnaissance survey of landslides triggered by the August 13, 1978, Santa Barbara, California, earthquake (M=5.1). Rockfalls from steep, artificial cuts appeared to be the most common type of landslide from this earthquake. The largest landslide noted was a rockfall in a roadcut on California State Highway 154, just south of San Marcos Pass. This failure involved about 100 cubic meters of debris and blocked the highway for some 30 hours. This rockfall occurred in the Sespe Formation, a weakly cemented tertiary conglomerate.

An extensive network of ground fissures was noted in a roadside "turnout" on Highway 154, 1/2 mile north of the landslide described above. The turnout was built on fill consisting of roadcut debris, deposited on a steep (>100%) canyon slope and is located in the Coldwater Formation. The fissuring of the turnout appears to have been induced by the ground shaking and, had the shaking been somewhat more intense or of a longer duration, might well have failed catastrophically.

A number of other small (<10 cubic meters) rockfalls were also noted in other roadcuts along Highway 154, especially in the Sespe and Coldwater Formations. No significant failures were noted in natural slopes. A number of small rockfalls were also noted in roadcuts along U.S. Highway 101 just south of Gaviota Pass. Again, no failures were noted in natural slopes. The only natural slope failures observed from this earthquake were a small number of very small (<5 cubic meters) rockfalls along the coastal bluffs near Goleta Point.

The derailment of a freight train along the Southern Pacific Railroad just west of Ellwood may have been caused by settlement of an embankment. A number of small slumps were noted along the embankment, but the reconstruction of the tracks had obscured any direct evidence of failure in the roadbed itself.

In summary, it appears that this earthquake, with a magnitude of 5.1 and located some 10 km offshore, may represent the "lower-bound" earthquake for which any significant seismic-induced landslides will occur in this area. Even so, rockfalls along steep roadcuts posed a significant hazard. Our observations suggest that artificially cut slopes are significantly more susceptible to seismic-induced failure than natural slopes in the same geologic materials. Had this earthquake been stronger, a number of severe failures would have occurred along the many steep roadcuts in the Santa Barbara area.

Reports

Hoose, S. N., Wilson, R. C., and Rosenfeld, J., 1978, Liquefaction-caused ground failure during the February 4, 1976, Guatemala earthquake: Proceedings of International Symposium on the February 4, 1976, Guatemala Earthquake and the Reconstruction Process, May 14-19, 1978, Guatemala City. (32 p.)

Harp, E. L., Wieczorek, G. F., and Wilson, R. C., 1978, Earthquake-induced landslides from the February 4, 1976, Guatemala earthquake and their implications for landslide hazard reduction: Proceedings of International Symposium on the February 4, 1976, Guatemala Earthquake and the Reconstruction Process, May 14-19, 1978, Guatemala City. (31 p.)

Wilson, R. C., Warrick, R. E., and Bennett, M. J., 1978, Seismic velocities of San Francisco bayshore sediments: American Society of Civil Engineers Specialty Conference on Earthquake Engineering and Soil Dynamics, Pasadena, Calif., June 1978, p. 1007-1023.

Harp, E. L., Wilson, R. C., Wieczorek, G. F., and Keefer, D. K., 1978, Landslides from the February 4, 1976, Guatemala earthquake: Implications for seismic hazard reduction in the Guatemala City area: International Conference on Microzonation for Safer Construction Research and Application, 2nd, San Francisco, Calif., Nov. 26-29, 1978. (in press, 12 p.)

Wilson, R. C., 1978, Discussion of "Shallow slides due to 1971 San Fernando earthquake" by Bing C. Yen and James R. Trotter: American Society of Civil Engineers Specialty Conference on Earthquake Engineering and Soil Dynamics. (Postconference volume in press. Director's approval, 4 p.)

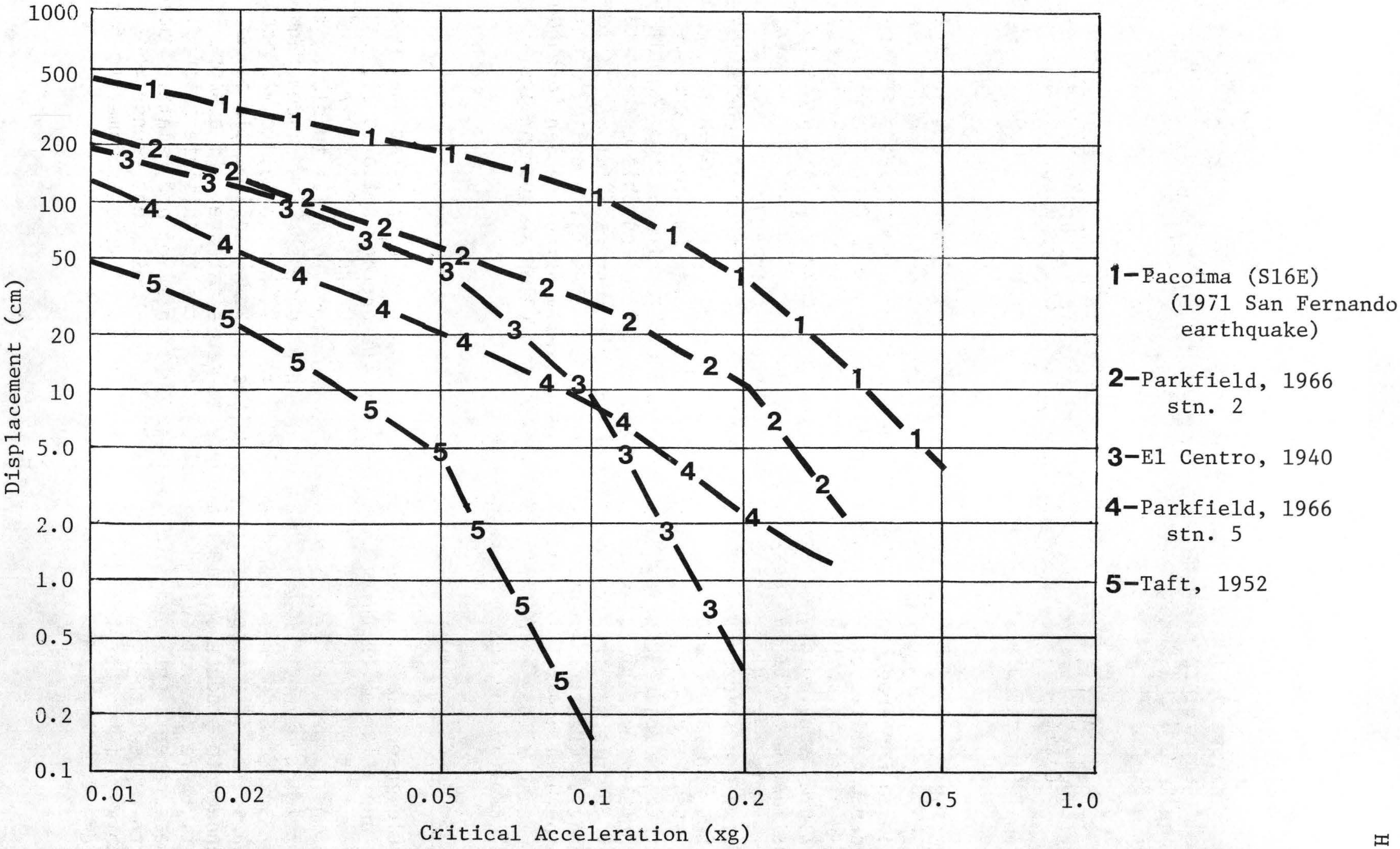

Figure 1.--Graphs of displacement versus critical acceleration for El Centro, Parkfield, Taft, and San Fernando strong-motion records.

SEMI-ANNUAL TECHNICAL REPORT SUMMARY
Contract No. 14-08-0001-G-512

SEISMICALLY INDUCED SHALLOW HILLSIDE FAILURES

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July 15, 1978

INTRODUCTION

The San Fernando Earthquake of 1971 resulted in numerous identified hillside slope failures. Of the several modes of slope failure which have been observed in San Fernando and in other seismically active areas of the world, shallow slides are by far the most common. This project deals exclusively with shallow slope failure.

Twenty-one slides were mapped in the general vicinity of Lopez Canyon in the San Fernando Valley, California. Soil samples were taken and tested, and analyses were made. The objectives of this research are to provide an engineering understanding of the slide mechanisms and to define the common characteristics of this type of slope failure. Based on this understanding, the goal of this research is to develop a simple but practical way to identify the potential location and estimate the size of slope failures in seismically active foothill areas. The project is essentially using the San Fernando event induced slides as a field laboratory to develop an appropriate analytical model to achieve the research objectives.

FIELD AND LABORATORY WORK

Field observations suggest that all slides have a translational mode of failure and a large length-to-depth ratio. The average ratio is 31, and the maximum is 80. The depth is generally on the order of 1 meter. The dips of the underlying beds are generally too steep relative to slopes to create sliding planes. Natural slopes which produce shallow slides range between 33 and 46 degrees, roughly 1-1/2:1 to 1:1, horizontal to vertical. It appears that if a slope is too steep, the residual soil mantle is not thick enough to produce an inertia force to cause failure. If a slope is too flat, there are not sufficient downslope forces to initiate sliding. Field measurements included slide geometry, orientation and relative location with respect to ridge top and foothill. No consistent trends were found between the occurence of the slide with any of these parameters for the slides studied.

No evidence suggests that any of the slides can be attributed to the direct displacement of a fault, rather they are the results of shaking.

A laboratory program to evaluate soil properties was initiated. Laboratory tests indicated that the slide materials are generally clayey or silty-sands of little or no plasticity (SC or SM) regardless of the parent geologic formation. This observation negates the earlier postulation that the distribution of slope failures is lithologically controlled, instead, in areas where bedrock is likely to weather into SM or SC soil, more shallow slides may be anticipated.

ANALYSIS*

Because of the low ratio of depth to length of the slides and their planar mode of failure, a one-dimensional mathematical model with an equivalent inertia term is used to account for the accumulative shaking effect causing failure. The model assumes an elastic soil layer bonded to a rigid plastic base. As all the cases studied failed during the 1971 earthquake, back calculations from surveyed and tested conditions are used to check the validity and applicability of the theoretical model for evaluating seismically-induced, shallow slope failures. To enable a rational comparison of field measurements with results of the theoretical approach, it is necessary to know properties of soils involved in the slides. The soil shear stress-strain relationships under low normal loads appear to be significant in choosing strength parameters for analyzing slope stability. The results of comparison between the field and the theoretical model suggest that the methodology developed and applied to the Lopez Canyon area shows promise for estimating the likely size of shallow slides. The estimated slide length could serve as a rational guide for decision makers and planners for use in seismically active foothill regions. The analysis also showed that conventional pseudo-static slope stability analysis, using a 0.1 or 0.2 constant acceleration, could be risky in assessing the potential of shallow seismic slides in Lopez Canyon.

There are physical and mathematical limitations of the proposed one-dimensional model. It is inevitable that some of the slides have been altered more than others since the 1971 earthquake. To broaden the data base and to improve the present technique, additional field mapping should be conducted immediately following future seismic events.

FUTURE PLAN

The slide features of the 21 studied slope failures triggered by the 1971 earthquake were supprisingly well preserved, probably because of the extended dry years since the San Fernando earthquake. However, the record-breaking heavy rain storms of this year obliterated nearly all traces of the

* A portion of this analysis has been published in a paper entitled "Shallow Slides Due to 1971 San Fernando Earthquake," Proceedings of the Earthquake Engineering and Soil Dynamics Conference, American Society of Civil Engineers, Vol. 2, pp. 1076-1096, June, 1978

original earthquake induced slides. Instead, hundreds of mudflows have occurred in the seismically weakened slopes and in the scarp areas of previous slides. The swift movement of mudflows in seismically weakened slopes appear to be even more hazardous in causing loss of life and interuption of lifelines. What is needed is a better geotechnical understanding of the mudflow mechanism in seismically weakened slopes. Simple but practical ways may then be developed to identify the location and to estimate the size of mudflows in seismically active foothill regions. A considerable amount of effort will be needed on this aspect which is beyond the scope of this project.

However, a preliminary slope stability analysis will be made using the soil samples available. The soil samples from the 21 mapped slides appear to be all that are left from the 1971 San Fernando event. Consequently, Lopez Canyon is a unique field laboratory that has both the pre-storm earthquake induced slides and the post-storm mudflows in seismically weakened slopes. In the remaining period of the research, additional tests will be made on these samples and limited field mapping will be done including the re-examination of the theoretical model.

Preliminary Assessment of Liquefaction Potential in and near San Juan, Puerto Rico

8-9510-00535

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Investigations

Began the preparation of a liquefaction potential map for the San Juan, Puerto Rico, metropolitan area. Geologic maps are being revised and updated. Geotechnical data are being collected and analyzed.

Results

Preliminary analyses indicate that with some updating and refining of geologic map units, existing maps of the San Juan area can be used in conjunction with geotechnical data, obtainable from public agencies and private geotechnical engineers, to prepare liquefaction susceptibility maps for the subject area. The second stage of the project, analysis of earthquake potential for compiling liquefaction potential maps, has not yet been initiated.

Reports

No reports prepared.

Experimental Mapping of Liquefaction Potential

8-9550-01629

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Investigations

1. Continued research on techniques for mapping seismically induced liquefaction potential.

2. Completed small scale liquefaction potential map of San Fernando Valley, California, in cooperation with John Tinsley, Branch of Western Environmental Geology and Dave Perkins, Branch of Earthquake Tectonics and Risk.

3. Continued work on liquefaction potential map of the San Juan, Puerto Rico, metropolitan area in cooperation with Watson Monroe, Branch of Eastern Environmental Geology. Geologic maps are being revised and updated as needed. Geotechnical data is being collected and analyzed.

4. Completed analyses and draft of a report on liquefaction during the November 23, 1977, San Juan, Argentina, earthquake for a forthcoming USGS Professional Paper on that earthquake. This report is coauthored by David Keefer, Branch of Engineering Geology.

Results

1. Mapping of liquefaction potential in the San Fernando Valley, California, revealed that areas most likely to contain sediments susceptible to liquefaction lie largely in the south and particularly the southwest part of the valley. Because of deep water tables, likelihood of liquefiable sediments in the central part of the valley are generally low to very low. From an analysis of earthquake potential in the region, it was estimated that the average return period for earthquake shaking strong enough to cause liquefaction in highly susceptible sediments in the valley is about 46 years.

2. Analyses of data collected during field investigations following the November 23, 1977, San Juan, Argentina, earthquake revealed the following: (a) The areal distribution of liquefaction was consistent with that of previous earthquakes. The greatest epicentral distance to an effect of liquefaction was 260 km which is the greatest distance yet recorded for a M=7.4 event, but is only marginally greater than would be predicted from the worldwide trend. (b) Nearly all of the sediments that liquefied during the earthquake were contained in Holocene flood plain and playa deposits. These types of deposits have proven to be highly susceptible to liquefaction during past earthquakes. (c) Five core samples were obtained from silt and sand sediments that likely liquefied during the earthquake. Densities of these specimens ranged from 1.35 g/cm^3 to 1.55 g/cm^3 indicating the packing is

relatively loose. (d) From measurements of sediment and water depths in a house in which sand boils erupted, it was found that 12.0 m^3 of sand and water came up into the house. Of that volume, there was 5.1 m^3 of bulk sand, 2.8 m^3 of solid sand particles, and 9.2 m^3 of water. These measurements yield a ratio of water to sand of 3:3 by volume and 1:3 by weight. This is the first time such volumes have been calculated.

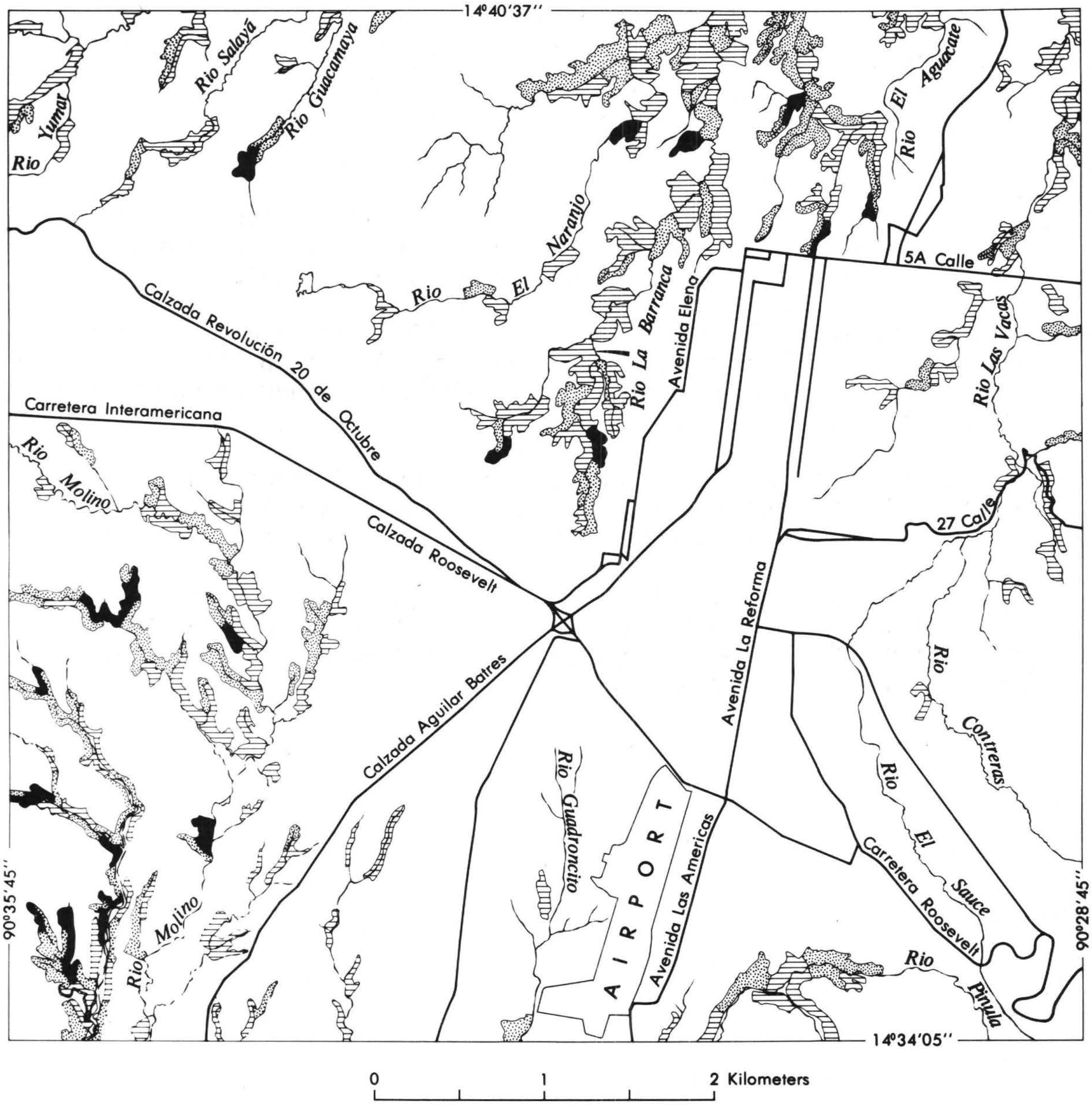
Reports

Youd, T. L., and Perkins, D. M., 1978, Mapping of liquefaction induced ground failure potential: Journal of the Geotechnical Division, American Society of Civil Engineers, v. 104, no. GT4, p. 433-446.

Youd, T. L., Yerkes, R. F., and Clark, M. M., 1978, San Fernando faulting damage and its effect on land use: American Society of Civil Engineers, Geotechnical Engineering Division Specialty Conference on Earthquake Engineering and Soil Dynamics, June 1978, Proc. v. 2, p. 1111-1125.

Youd, T. L., and Keefer, D. K., 1978, Liquefaction and landslides in the November 23, 1977 earthquake in San Juan Argentina [abs.]: Geological Society of America, Abstracts with Programs, v. 10, no. 3, p. 521.

Youd, T. L., Tinsley, J. C., Perkins, D. M., King, E. J., and Preston, R. F., 1978, Liquefaction potential map of San Fernando Valley, California: International Conference on Microzonation for Safer Construction, 2nd, San Francisco, 1978, in press.



EXPLANATION

Landslide concentration (in percent)

0 - 5 Low	5 - 20 Moderate	20 - 50 High	>50 Severe

Statistical Analysis and Geometry of Surface Faulting

8-9940-02086

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Investigations

1. Compilation and evaluation of data related to historic surface faulting, such as fault length and displacement, the distribution of subsidiary faults, and the magnitude, seismic moment, and focal depth of associated earthquakes.

2. Statistical analyses of the relations between and among the data listed above.

3. Statistical characterization of the variation in displacement and surface width as a function of position along the main fault.

4. Statistical characterization of the location, orientation, and displacement of subsidiary faults with respect to the main fault.

5. Bonilla is primarily responsible for compilation and evaluation of the data and R. K. Mark is primarily responsible for the statistical analyses of the data.

Results

1. Because subjectively assigning quality estimates to reported fault data resulted in better correlation coefficients in regressions of earthquake magnitudes on length and displacement, a more objective estimate of errors is in progress. About 50 events have been reviewed, and it was possible to assign estimates of probable errors to about 25 of those events. Estimates were based, to the extent possible, on comparison of various reports on the same event, the thoroughness of the investigation, the conditions for observation, aftershock patterns, and geodetic data.

2. With the help of W. H. K. Lee, magnitudes assigned by various observatories to earthquakes associated with surface faulting were compiled, compared, and an estimate made of the errors in reported magnitudes.

3. Published data on focal depths of earthquakes associated with faulting were compiled and error estimates made by J. J. Lienkaemper and checked and revised by Bonilla. Published focal depths for main shocks were used when available, supplemented by aftershock data, published analyses of fault widths based on geodetic surveys, focal depths characteristic of the area and, as a last resort, depth based on distribution of intensity. More than 95 percent of the events for which an estimate was made had focal depths of less than 25 km.

4. Displacement as a function of distance along the main fault was digitized by E. B. Newman for several events. For the events that have been digitized, the amount of displacement characteristically has an irregular sawtooth pattern with two or more conspicuous peaks, and the median displacement ranges from about one-tenth to one-third of the maximum displacement.

5. Digitizing the main and all subsidiary faults of the 1957 Gobi-Altai event was completed by E. B. Newman. For this event the incidence of subsidiary faults does not decrease uniformly with distance from the main fault but instead is greatest at about 5 km and 20 km from the main fault. Orientation of the subsidiary faults with respect to the main fault suggests that the branch faulting was predominantly in the direction of Riedel shears and the secondary faulting was predominantly in the direction of P-shears.

6. Review of the statistical problems associated with regression of earthquake magnitude (M) on surface fault length (L) and displacement (D) was continued. Possible underlying models that were considered included: a) a deterministic relation between M and L with scatter in data due to measurement errors, b) a stochastic relation between M and L, further complicated by measurement errors. Statistical modeling techniques being applied include: a) ordinary least squares, b) bivariate normal distribution, c) multivariate least squares (including for example M, L, D, and focal depth), d) instrumental regression, and e) weighted least squares.

Reports

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Bonilla, M. G., Alt, J. N., and Hodgen, L. D., 1978, Trenches across the 1906 trace of the San Andreas fault in San Mateo County, California: U.S. Geol. Survey Jour. Research, v. 6, no. 3, p. 347-358.

R. Goodman, Principal Investigator

SEMI-ANNUAL RESEARCH REPORT

for Grant 14-08-0001-G-507
University of California, Berkeley

DEVELOPMENT OF TECHNIQUES FOR EVALUATING SEISMIC HAZARDS ASSOCIATED WITH EXISTING CREEPING LANDSLIDES AND OLD DAMS

S U M M A R Y

Two areas are under study. In the first, a tool is being developed to permit the pressure versus deformation relations of rock foundations to be measured while the location of fractures in the region of measurement is surveyed precisely. The latter makes it possible to obtain a meaningful estimate of the deformability properties of the foundation, taking into account the actual fractured condition of the rock. This tool will then be used to obtain information vital to analysis of old dams under simulated earthquake loadings. The instrument now under construction consists of a rubber packer which spreads opposed aluminum bearing plates against the borehole wall; the bearing plates are coated with a wax film which squeezes into fractures providing an impression map of the walls. The expansion of the rubber packer is to be measured by several direct and indirect techniques and the pressure is measured with a Bourdon gage. The instrument is currently under construction at Imperial College, London, England, and will be shipped to Berkeley in the late summer.

The second area concerns the measurement of creep rates in stable and unstable hillsides using a sensitive creep meter and continuous monitoring system. An existing instrument, intended for short creep lines in tunnels and for brief monitoring periods has been made to work for lines as long as 100 feet over continuous monitoring periods of more than

two weeks. In definitely actively sliding slopes, creep rates measured varied between 1.03 and 0.07 thousands of an inch per hour. The sensitivity of the instrument is of the order of a ten thousandth of an inch, implying strain rates over the 100 foot base length of the order of 10^{-7}. The field tests and procedures by which slope creep has been separated from environmental and system effects unrelated to instability are described in detail in the report. The goal of this research is to provide a technique by means of which definitely unstable areas can be documented as such without large investments for instrumentation so that seismically dangerous areas can be isolated.

Seismological Field Investigations

8-9950-01539

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Investigations

1. Argentina aftershock study--regional investigation of the aftershocks of the magnitude 7.1 (M_s) western Argentina earthquake of Nov. 23, 1977, approximately 90 km northeast of San Juan.

2. Greece aftershock study--detailed investigation of the aftershocks of the magnitude 6.4 (m_b) earthquake of June 20, 1978, which occurred in northern Greece, approximately 30 km east of Thessaloniki.

3. Peru aftershock study--completed analysis of data obtained from the magnitude 7.8 (M_s) Peru earthquake of October 3, 1974.

4. Texas aftershock study--detailed investigation of aftershocks resulting from the magnitude 4.75-5.0 (M_L) Scurry County, Texas, earthquake of June 15, 1978.

Results

1. The magnitude 7.1 (M_s) western Argentina earthquake of November 23, 1977, occurred at the northern end of Sierra Pie de Palo, approximately 90 km northeast of the city of San Juan. Sierra Pie de Palo and the surrounding area is a region of considerable geomorphic and geologic complexity. The Sierra Pie de Palo as well as the neighboring Sierra del Valle Fertil and Sierra de la Huerta to the east are mainly composed of Precambrian metamorphic and intrusive rocks which have a predominant north-south trend. These mountains rise to more than 3,000 meters above sea level, whereas adjacent valley floors are 500-700 meters in elevation. The Precambrian mountains are generally bounded by northerly striking faults; however, extensive crosscutting of east-west faults is also present. A large northerly trending basin to the north, east, and south of Sierra Pie de Palo contains over 6 km of Pleistocene and Holocene sediments.

Most of the aftershock epicenters occur along the eastern half of Sierra Pie de Palo and in the basin to the east and south. The network of nine portable seismographs, which was deployed to record the aftershock activity, surrounded the main shock rupture zone to the extent allowed by surface vehicular access. Five stations were located on Precambrian rocks, one site on Tertiary stratum, and three instruments were placed on the basinal alluvium. Because of the obvious near-surface variations in seismic velocities present in the aftershock epicentral region (Holocene alluvium to Precambrian intrusives), seismograph-station corrections were computed for each of the nine seismograph locations following the development of a generalized seismic velocity model for the study area.

The regional P-wave velocity model was developed from reversed refraction profile data obtained from Yacimientas Petroliferous Fiscales (YPF) and from well-log data provided by Cities Service Company. Sufficient information was made available so that the top of the Precambrian "basement" could be contoured in terms of depth and velocity. Average sedimentary-column velocities (one-way vertical travel-times) were calculated at the center point of each refraction profile, contoured, and the results combined with the depth-to-basement values to obtain vertical sedimentary travel-time estimates for the study area (0.0 s to more than 1.5 s is indicated). The region was then grided at quarter-degree intervals. At each of the resulting 45 grid points, average sedimentary velocity, sedimentary thickness, and Precambrian velocity were determined by interpolation between the contoured values. Averages were obtained for each of the above parameters to produce the generalized P-wave velocity model of the sedimentary and Precambrian section (2.87 km/s from 0.0 to 2.4 km; 5.88 km/s from 2.4 to 10 km). To complete the model, velocities of 6.2 km/s from 10 to 32 km, 7.3 km/s from 32-55 km, and 8.1 km/s below 55 km were assumed. It was noted, during the foregoing analysis, that average velocities in the sedimentary column exhibited variations from about 2.5 km/s to more than 4.0 km/s. Also, velocities at the top of the Precambrian were found to vary from 5.3 km/s to 6.2 km/s.

Station corrections were determined from the contoured "actual" travel-time values, which were determined by the previously mentioned average sedimentary column velocities and depth-to-basement calculations. The difference between the "actual" and generalized velocity model travel-times were then considered to be station corrections. These corrections range from -0.30 s (station on basinal alluvium) to +0.5 s (station on Precambrian intrusives).

Approximately 150 aftershock hypocenters have currently been located in a north-trending zone that extends between about 31° and 32° S. lat. The east-west limits of this zone are primarily confined between 67.5° and 68° W. long. The general depth range is between 15 and 50 km, with the deeper aftershocks occurring to the west under the Sierra Pie de Palo.

2. The magnitude 6.4 (m_b) northeastern Greece earthquake of June 20, 1978, occurred approximately 35 km east-northeast of Thessaloniki. The main shock was preceded by two intermediate magnitude foreshocks that took place on May 24, 1978 (m_b=5.7), and June 19, 1978 (m_b=5.4). A ten-station network of portable seismograph systems was installed around the epicentral region of these earthquakes one day prior to the occurrence of the largest aftershock (m_b=5.0). Eighty-four aftershock hypocenters have been located to date; they occupy a west-northwest trending, elliptical-shaped zone that is approximately 20 km long and 12 km wide. Depths of the aftershocks are principally confined between 5 and 10 km.

The focal mechanism for the mainshock, determined from regional short-period P-wave first-motion data (B. C. Papasochos and G. Leventakis, written commun.), indicates left-lateral strike-slip motion along a near-vertical plane that strikes N78° W. Preliminary composite focal mechanism solutions, computed from the locally recorded aftershock data, are largely consistent, in both strike and dip, with the focal mechanism of the main shock. However, some aftershocks at the eastern end of the aftershock zone show a reverse faulting mechanism which strikes to the northwest at approximately 45°.

3. All aftershock hypocenters determined from regional and teleseismic data following the Peru earthquake of October 3, 1974, have been relocated by J. W. Dewey, using the combination of joint hypocenter determination (JHD) and master event methods. The comparison between Dewey's hypocentral locations (those made from regional data and data recorded teleseismically for some events), and the hypocenters determined by the HYPO71 computer program (those made from regional data only) show, for the most part, only small relative changes in epicenter and depth. For the general case, the epicenters were moved to the north and east by approximately 5 km and depths were changed about ±8 km. Therefore, Dewey's analysis supports the previous results obtained by use of HYPO71 and the regional aftershock network data.

4. The three recent earthquakes (M_L = 4.0 on June 7, 1977; M_L = 3.5 on November 28, 1977; and M_L = 4.75-5.0 on June 16, 1978), which occurred near Snyder, Texas, were located in an area where no previous seismic activity had been reported. Fourteen aftershocks of the June 16, 1978, earthquake were recorded by a 10-station network of portable seismograph systems. Installation of the network, which was operational for a 10-day period, began approximately 18 hours following the main shock. Sufficient data were obtained to locate eight aftershock hypocenters, which ranged in magnitude from 1.0 to 3.0 (M_L) and occupied an area 2.3 km long by 2.0 km wide. The aftershock focal depths ranged from about 1 to 5 km. This seismic activity occurred at the north end of the Scurry oil field in Scurry, Kent, and Borden Counties, roughly 140 km northeast of Midland, Texas. Parts of the oil field were undergoing large-scale water flooding at the time of the recent earthquakes, with well-head pressures between 145 and 221 bars.

The historical absence of seismicity observed for this region, coupled with the occurrence of earthquakes within an oil field that is being injected with water at high pressures, suggest that the earthquakes and aftershocks were induced by the oil field activities. A study, to be lead by S. T. Harding and funded by the induced seismicity project, will further investigate the local seismicity.

Reports

Harding, S. T., Carver, David, Henrisey, R. F., Dart, R. L., and Langer, C. J., 1978, The Scurry County, Texas, earthquake series of 1977-1978--Induced seismicity? [abs.]: Seismological Society of America, 50th Ann. Meeting, Eastern Section, Program and Abs.

CONSEQUENCES OF AN EARTHQUAKE PREDICTION ON STATISTICAL ESTIMATE OF THE SEISMIC RISK

U.S.G.S. Grant No. 14-08-0001-G-501

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Summary of Semi-Annual Technical Report

This contract requires two major steps: first, derivation of a base seismicity model for the Los Angeles Basin and second, estimation of the seismic risk for the base model and for modifications to the base model caused by "predictions." The first step is complete, and the second step is underway.

The base seismicity model was derived by the use of slip rates on faults in southern California. This was done because the historical record of earthquakes is considerably shorter than the recurrence time on most of these faults. The slip rates for most southern California faults are not well known, but in many cases, the geological data allow an estimate of the range of possibilities (Anderson, 1978). Figure 1 shows a model which is consistent with much of the geological literature, as summarized by Anderson. Slip rates in Figure 1 can be converted to occurrence rates by the use of the method of Brune (1968) and of others, and by assuming a distribution function over magnitudes. The resulting seismicity model has been compared with the historical seismicity, and for the region taken as a whole, the agreement is good. For individual faults, of course, the agreement is not good in general. The seismicity model, and the checks on its adequacy, are described in detail in Anderson (1978).

Seismic risk analysis of Los Angeles based on this seismicity model, and on this model combined with possible "predictions" is underway.

References

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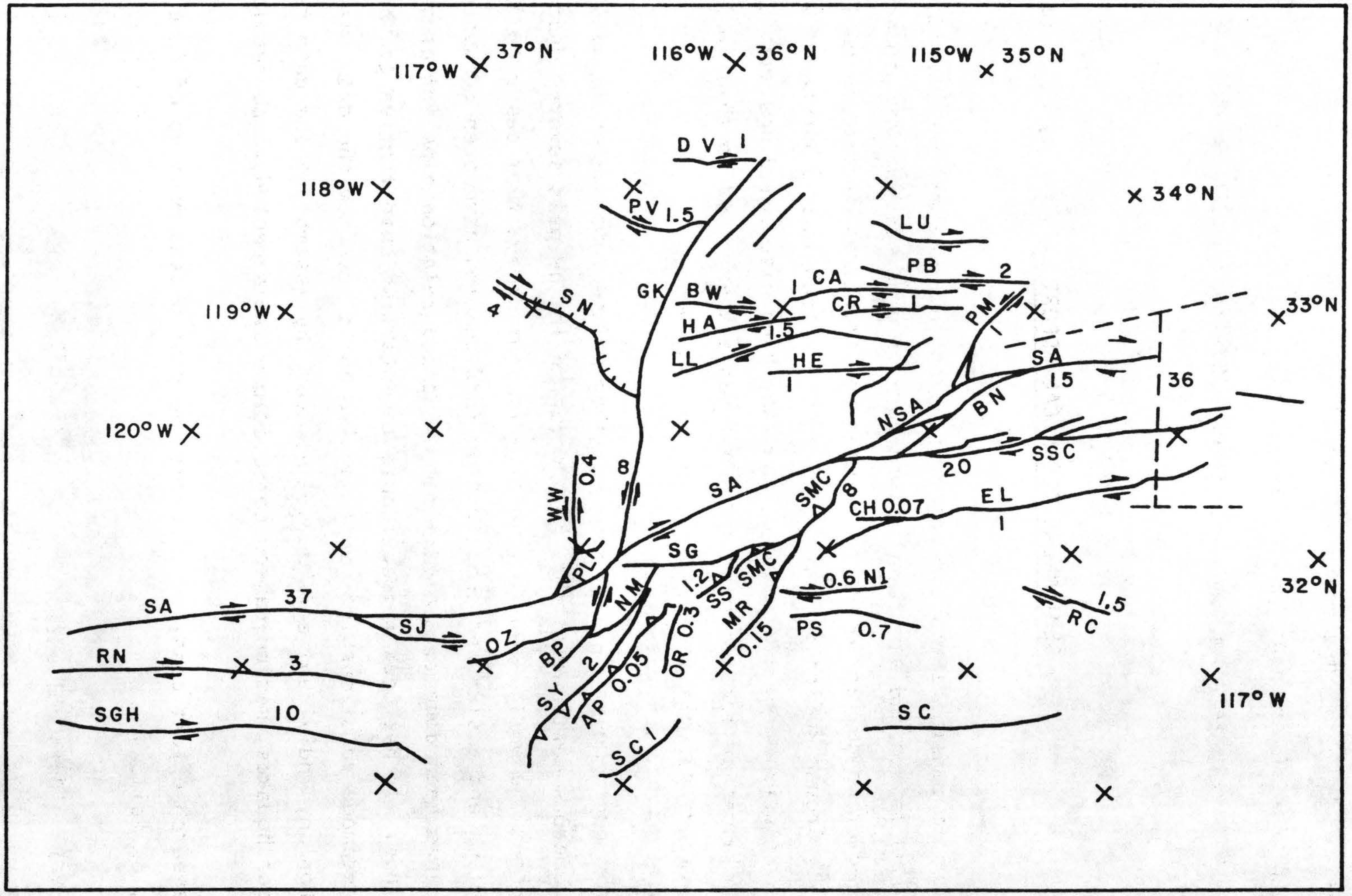

Figure 1

Slip rate consistent with geological data for faults in southern California

H.C.

TITLE: SEISMIC DAMAGE ASSESSMENT FOR HIGH-RISE BUILDINGS

PRINCIPAL INVESTIGATOR: Roger E. Scholl

CONTRACTOR: URS/John A. Blume & Associates, Engineers

DATE: October 1978; Contract no. 14-08-0001-16814

SUMMARY

SEMIANNUAL TECHNICAL REPORT

The problem considered is the identification, evaluation, and correlation of ground motion and structural parameters in order to improve procedures for predicting dollar losses for high-rise structures damaged by earthquakes. Ground motion data bases, analytical techniques, and known motion-damage relationships already developed for high-rise buildings and for other classes of structures will be refined and extended so that reliable quantitative seismic risk evaluations can be made.

A significant amount of high-rise building damage information is available from numerous earthquakes that have occurred in the past several decades throughout the world. While investigations of damage that describe failure mechanisms and design and construction inadequacies have been conducted, little has been done to evaluate motion-damage relationships for high-rise buildings. It has been impracticable to establish quantitative ground motion-damage relationships for high-rise buildings from the data available for any individual earthquake; however, by assembling the data from many earthquakes, motion-damage correlations are expected to be feasible.

The research effort consists of three one-year phases made up of five major tasks, as follows:

Task I Data collection

Task II Building categorization and calculation of theoretical motion-damage relationships

Task III Estimation of engineering intensity from seismological intensity data

Task IV Evaluation of empirical motion-damage relationships

Task V Correlations between theoretical and empirical motion-damage relationships.

Task I is scheduled to be completed during the first year. Tasks II and III will be initiated during the first year and are scheduled to be completed during the second and third years. Tasks IV and V will be initiated during the second year.

The objective of Task I is to establish a data base of worldwide seismic response and damage data for high-rise buildings. Five different forms have been developed to systematically collect the pertinent data. Form 1 gives information about each earthquake considered, while Form 2 describes the effect of the earthquake at a specific site. The site geology and building characteristics are described on Forms 3 and 4, respectively. Detailed information, such as test boring logs or design calculations, is attached to Form 5.

All the earthquakes selected for study affected high-rise structures. For administrative functional and technical reasons, the data collection effort has been divided into the following areas: North America; Latin America; Europe and the Mediterranean; and the western Pacific, which includes Japan and New Zealand. The general information on Form 1, including magnitude, intensity, and overall damage estimates, has been collected for the earthquakes selected in each of these regions. The collection of data concerning specific building sites in major urban areas affected by these earthquakes will be completed in the final months of this year.

One of the major items that must be considered in the evaluation of high-rise building damage due to ground motion is the categorization of the buildings. The building categorization part of Task II will be completed this year. Structural systems considered in this categorization are foundation systems, vertical load-support systems, lateral load-resisting systems and floor systems. The most notable of these are the lateral load-resisting systems. The materials used in the construction of buildings are also an important part of building categorization. Both structural and architectural materials are considered. Architectural materials, although not designed specifically to resist the lateral loads, contribute in varying degrees to this resistance and are important for damage evaluation. The degree of contribution depends not only on the type of architectural material used, but also on the framing characteristics of the building systems. Another item considered is the configuration of the building. Because of the irregularity of the building plan and elevation, a building may undergo torsional response. Torsional response also may result from eccentric location of either the building masses or the lateral load-resisting elements. Data collection Form 4 was developed to appropriately record each of these items of information for buildings.

Substantial progress has been made towards relating seismological intensity to engineering intensity (Task III). Initial results have been compiled based on published data available from the San Fernando 1971 earthquake, and conclusions have been drawn. It is evident that additional consideration should be given to international data and various seismological and geological factors (Tasks IV and V). The available international data base has been identified. Distance, magnitude and local geology will be considered as the primary seismological and geological factors in relating seismological intensity to engineering intensity. Distance is defined as the shortest length from the recording site to the fault plane. It will be broken up into categories: for example, less than 25 km and greater than 25 km. Magnitude will be classified in the following bands: $M < 5.0$; $5.0 \leq M < 6.0$; $6.0 \leq M < 7.0$; or $M \geq 7.0$. Local geology will be specified as one of the following: soft alluvium deposits, intermediate (hard sedimentary) rock, or basement (crystalline) rock. The effects of earthquake duration will also be considered.

Research Applications

8-9900-90027

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Investigations

1. Development of a workshop to examine the process of communicating earthquake hazard reduction information.

2. Establishment of an effective communication process between producers of information in the Earthquake Hazards Reduction Program and users in the federal, state, and local government; academic; and private sectors.

Results

1. A 2 1/2-day workshop was convened in Denver, Colorado on May 22-24, 1978. Sixty-five people with varied backgrounds participated in the workshop. They examined the communication process developed in a dozen case histories and identified the lessons that were learned about how to achieve effective communication. General recommendations for improving communication were generated during the course of the workshop. Some of these recommendations will be adopted in the USGS Earthquake Hazards Reduction research program. A conference proceedings was developed and published following the workshop.

Reports

Hays, W. W. (editor), 1978, Proceedings of Conference V, Communicating Earthquake Hazard Reduction Information, Geological Survey Open-File Report 78-933, 420 p.

Heat Flow and Tectonic Studies

8-9960-01176

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Investigations

1. Heat flow and tectonics in the southern Basin and Range province. Thirty plus holes were drilled in granitic rocks of the Arizona Basin and Range and one in sedimentary rocks of the southern Colorado Plateau.

2. Heat flow and tectonics of the Mojave Block. Lab and numerical work was completed, and an abstract submitted to the fall AGU. Nine holes were drilled near the Garlock Fault in the Randsburg area to delineate a geothermal anomaly.

3. Heat flow and tectonics of the northern Great Basin. Final temperature logs were obtained from the holes drilled in 1977. Thirteen holes were drilled in the Black Rock Desert to evaluate a prospective geothermal resource and to obtain heat-flow data near the Black Rock Fault.

4. Thermotectonics of the San Andreas Fault Zone. Permits were obtained to drill 30 holes in the northern Coast Ranges between latitudes 39° and 41° N. To date, 10 of the holes have been drilled.

5. Heat flow and tectonics of Alaska. Temperature data were obtained at about 20 sites throughout the state by Larry Lawver and Tom Moses. Lawver also acquired geologic information and rock samples for the ten or so sites in bedrock terranes.

Results

1. Based on fragmentary data available from western Arizona, the range and mean of heat-flow values from this part of the Basin and Range province seem consistent with those for the remainder of the province.

2. Little or no correlation is found between heat flow and radioactive heat production in the region extending from the San Andreas and Garlock faults eastward to Arizona. Within the Mojave tectonic block, heat flow is relatively uniform with a mean value of about 1.6 HFU ($\sim$70 w/m^2). Such values persist up to and across the San Andreas fault which forms the block's southwest boundary; no local anomaly is found at the fault. Toward the east the heat flow rises sharply along a NNW-trending boundary that coincides with the easterly limit of active seismicity and a change from predominantly strike-slip to normal faulting. The average heat flow east of this boundary

is about 2.1 HFU (90 w/m^2), similar to the average for the Great Basin. A conductive heat-flow anomaly about 20 km long and 10 km wide is associated with geothermal manifestations near Randsburg, south of the Garlock fault. Because of the background heat flow in this region, we are selecting additional sites to test the possibility of a narrow heat-flow anomaly associated with the Garlock fault.

3. Preliminary interpretation of the 1977 results suggest some minor modifications to the NW boundary of the Battle Mountain high, but otherwise our previous interpretation of the northern Great Basin will not change significantly. The Black Rock Desert heat-flow survey was the first successful deployment of our downhole heat-flow probe, a significant advance in the technology of measuring heat flow in unconsolidated sediments. There seems to be a significant heat-flow anomaly associated with the Black Rock fault, a contemporary extensional feature.

4. Very preliminary results from drilling in the northern Coast Ranges near Eureka, California, suggest low-to-normal heat flow in contrast to the generally elevated heat flow in the Coast Ranges between Point Reyes and Bakersfield.

5. Data from Alaska are being reduced; results are not yet available.

Reports

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In Situ Stress Measurement Project

8-9960-01184

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Palmdale Studies:

Stress measurements were completed in a profile of 250 m deep wells drilled perpendicular to the San Andreas fault near Palmdale, California. Horizontal shear stress was observed to increase with distance from the San Andreas. The result of modelling these data suggests that the magnitude of the shear stress acting on the San Andreas fault in the upper 20 km of the crust averages about 100 bars. The direction of maximum horizontal compression in the region was found to be about N10°W.

Induced Seismicity Studies:

Measurements of in situ stress, pore pressure, and permeability were made to depths of 1 km in a well drilled adjacent to Monticello Reservoir, near Jenkinsville, South Carolina. The well was drilled adjacent to the lake into a cluster of shallow earthquakes occurring less than 1 km deep. The measurements document the manner in which the reservoir is raising the ambient pore pressure. Moreover, the measurements establish that the change in pore pressure is sufficient to trigger thrust type earthquakes in the near surface. The mechanism of earthquakes occurring in the area at depths of 2-3 km is as yet unknown.

New Madrid Studies:

Drilling began of a 900 m deep well in the New Madrid Seismic Zone. The primary purpose of the well is to make stress measurements in Paleozoic rock underlying Mississippi embayment sediments at a depth of approximately 600 m.

Interpretation of seismic reflection profiling in the vicinity of Reelfoot Lake, Tennessee was completed. This work established the existence of Late Cretaceous, or older, faults that have been reactivated in Late Holocene time.

Reports

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UNIVERSITY OF SOUTHERN CALIFORNIA

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Contract No. 14-08-0001-16745

DEEP-WELL MONITORING OF STRAIN-SENSITIVE PARAMETERS OVER THE GREATER SOUTHERN CALIFORNIA UPLIFT

Twenty deep well sites are now available for research in the area of the "Southern California Uplift." Some of the major current research efforts making use of these sites include:

1. Groundwater radon-chemistry studies. A study of the chemistry of groundwater collected for radon analysis has been carried out with two goals: (a) to see if major element chemistry may act as an earthquake precursor. A change in the flow path of movement rate prior to an earthquake may result in a change in the chemistry at a monitoring site, and (b) to search for simultaneous changes in chemistry and radon-222. Radon has been utilized as a tool to predict earthquakes by Chinese and Russian programs, but all radon variations do not reflect changes in the stress field. Simultaneous analyses for radon and major element chemistry may reveal radon fluctuations which are due to changes in rainfall or flow patterns.

The following conclusions have been reached during the past year: (a) Shallow wells show significant changes in major element chemistry and/or radon as recharge rates vary. Thus, major element chemistry may be useful in sensing a change in groundwater flow rates or patterns prior to an earthquake. It has not been established whether or not chemistry is likely to be a more sensitive indicator of flow patterns and rates than other techniques such as water level; (b) Clearly different mechanisms must control the chemistry and radon observed in deep wells. In one well, an increase in recharge caused radon to decrease with no change in chemistry. In another, an increase in recharge diluted waters but did not affect radon. In general, radon did not correlate with any elements in wells of any depth and it is concluded that major element chemistry and radon respond to different perturbations; (c) In deeper wells, small variations in chemistry can occur which show coherence among different elements. Although the nature of the perturbation mechanism has not been identified it is important to see that wells of these depths may show somewhat variable chemistry, apparently on a seasonal basis.

2. Acoustic emissions. This system is designed to observe and study the nature of crustal acoustic emissions within the frequency band 20 Hz to 16 Khz. Downhole sensing is accomplished with the aid of a hydrophone. Several sequences have been recorded, including many high frequency bursts. Also, microearthquake activity has been recorded in the Palmdale area.

3. U.S.C.-Princeton Cooperative Airgun Experiment. A 1000 cubic inch airgun in Bouquet Reservoir, 25 km west of Palmdale, California, provides a reproducable seismic signal that is stacked to give a ±3 msec accurate travel time over a 20 km path between reservoir and any of a set of instrumented boreholes. Telephone lines link the boreholes and the reservoir, where a computer automatically fires the airgun and collects, processes and stores the travel time data. A shot stack comprises 50 to 100 shots; at current compressor power, this yields a travel time data point every 2 to 4 hours. Our inital data set consists of 13 points for one borehole. It shows mild scatter in travel times with excursions about the mean value of 3758 msec of up to 8 msec (3 standard deviations).

Prediction Monitoring and Evaluation

8-9920-02141

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Investigations

1. This project monitors and evaluates earthquake predictions from any source. The intent is to provide statistical evaluations of any author making such predictions which can be used in answering questions from the public about such authors. Approximately 2000 earthquake predictions from over 200 different authors were collected and evaluated. Of these, statistical tests show that only one was above the 1% level which is to be expected, considering the number of authors examined.

2. The computer programs used in connection with the project have been re-written to improve running speed and efficiency.

Results

1. Since the majority of individuals are so far below chance expectation, predictions from non-scientists will no longer be evaluated. Such predictions will be accepted and filed for future reference if needed. All predictions through 1977 have been evaluated and a final report will be prepared. In the future the program will concentrate on scientific predictions as they become available.

2. The current version of the scoring program is approximately 8 times faster than the original version.

Reports

Hunter, Roger N., and Derr, John S., 1978, The Prediction Monitoring and Evaluation Program: A Progress Report, Earthquake Info. Bull., v. 10, no. 3, p. 93-96.

Interpretation of Geophysical Data for Earthquake Prediction

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30 October, 1978

Summary

We have developed statistical techniques for testing hypothetical anomalies in seismic, geomagnetic, tilt, and strain data. We have examined some of each kind of data and have found no conclusive evidence for anomalies related to tectonic activity. We have made theoretical investigations of methods of analyzing leveling data, methods of including constraints and prior information in underdetermined inverse problems, and in seismic ray tracing.

We studied P wave phase arrival times for southern California local earthquakes, 1972-74. These years were selected for special study because of the reported observations by Whitcomb (1975, personal communication) of changes in the apparent V_p/V_s ratio during that period. We developed a travel time model to account for lateral velocity variations, and we developed a statistical model for data errors that is consistent with the observations. We found no significant evidence of any temporal variation in P residuals. Furthermore, we found that errors in the travel time data are large and non-Gaussian. Temporal velocity variations could be reliably identified only if they were huge. The errors will also affect any determination of the V_p/V_s ratio using the Wadati technique, causing an error in the estimation of V_p/V_s ratios that may be several times the formal uncertainty. We conclude that the apparent V_p/V_s variations observed by Whitcomb were artifacts of the random errors in the data.

We examined USGS geomagnetic data from the central California total field array using a modified form of the technique of Poehls and Jackson (1978). Effects of geomagnetic disturbances in the atmosphere and of the associated induction in the crust were estimated from the vector field data at the Castle Rock observatory. These were subtracted from the data, leaving a residual difference field which was scanned for evidence of tectonomagnetic effects. Recent modifications of the technique facilitate design of the transfer function in the time domain. The rms residuals in hourly averages of the corrected magnetic field are as small of 0.4 γ.

We began a study of existing geodetic strain and tilt data to develop an optimum strategy for measuring crustal deformation of tectonic origin. We examined tiltmeter data from both the USGS bubble level devices in central California and water tube tiltmeters in Japan. In both cases meteorological effects, especially rainfall, seem to be the dominant noise source. Attempts to correct

the California tilt data for rainfall using a linear filter have been only marginally successful; variations remain, and there is evidence for nonlinear effects. In the Japanese data, we find a strong seasonal component in both extension and tilt, with good phase correlation throughout Japan. The source of the variation is currently unknown. Although part of the effect may be due to residual temperature effects, this suggestion does not explain the phase correlation.

We made a theoretical study of the analysis of leveling data to obtain uplift rates as a function of geographic location. We developed a formulation for finding the optimum uplift rate function in the general case when the repeated leveling surveys are incomplete and protracted in time. We find that errors in the initial reference survey must be included to give an accurate estimate of the errors in the estimated uplift rate. If these are neglected (that is, if the reference "terrain" is assumed fixed), then errors in the calculated uplift rates may be strongly underestimated.

We have studied ways in which physical constraints and prior information may be used to improve the resolving power in underdetermined inverse problems such as the determination of seismic velocities from arrival time data. Often prior information may simply be weighted according to its uncertainty and treated as experimental data. Inclusion of prior data frequently makes underdetermined problems overdetermined and is formally equivalent to the use of stochastic inversion or generalized inversion in some important cases.

We studied the linearity of seismic travel times as a function of seismic slowness to determine whether explicit ray tracing is needed in velocity inversions. Errors in the linear assumption were less than 0.1 sec if slowness perturbations were less than 5% in the cases studied. Nonlinear effects cause biased errors (the linear approximation is always late). In general explicit ray tracing should be used if biases of 0.1 sec cannot be tolerated, unless the initial slowness model is known to be correct to within 5%.

Publications under this Grant

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Seismicity Studies at Lake Jocassee, Lake Keowee and Monticello Reservoir, South Carolina (October 1977 - March 1978)

Summary of Semi-Annual Report
Contract No. 14-08-0001-14553

by

Pradeep Talwani and others
University of South Carolina

1. <u>Monitoring Seismicity at Lake Jocassee</u> (October 1977 - March 1978)

In this period 315 events were recorded (or an average of about two events per day), of these 241 were located and 139 with RMS $\leqslant 0.05$ sec, ERH, ERZ $\leqslant 1$ km are plotted in Figure 1. The largest event in this period was a M_L 2.2 event on November 25, 1977, located to the north of the lake. (This event was successfully predicted). The seismicity was found to be concentrated near the lake, with a noticeable increase in hypocentral depths with three events being deeper than 4 km.

Discrete radon monitoring at one site indicated that some radon variations are seasonal with a period of about 47 weeks.

2. <u>An Earthquake Prediction at Lake Jocassee</u>

In the time period of this report there was a M_L 2.2 event on November 25, 1977. The magnitude (±0.2) and occurrence time (within ~ 1 day) were successfully predicted on the basis of a t_s/t_p anomaly (Figure 2).

3. <u>Amplitude Ratios and Polarity Changes as Earthquake Precursors</u>

P/S_V amplitude ratios and P-wave polarities at different stations were examined for foreshocks and aftershocks (of three events) lying in a narrow cluster for an evidence of precursory changes. No systematic precursors were found. However a marked reversal was seen in the polarity at two stations before the September 7, 1977 event (Figure 3).

4. <u>Keowee Earthquake Swarm</u>

An earthquake swarm occurred in the vicinity of Lake Keowee in January 1978. At its most intense there were up to 200 events per day, with the larger events $2.0 \leqslant M_L \leqslant 2.5$. The shallow activity was concentrated in a NW - SE zone (Figure 4) and was possibly triggered by solid earth tides.

5. <u>Seismicity near Monticello Reservoir</u>

In a relatively aseismic region, seismic activity followed by about 3 weeks the impoundment of the Monticello reservoir (December 1977 - February 1978) (Figure 5). The seismicity is located in two broad east west zones, which are associated with migmatite zones around granite and granodiorite plutons (Figure 6).

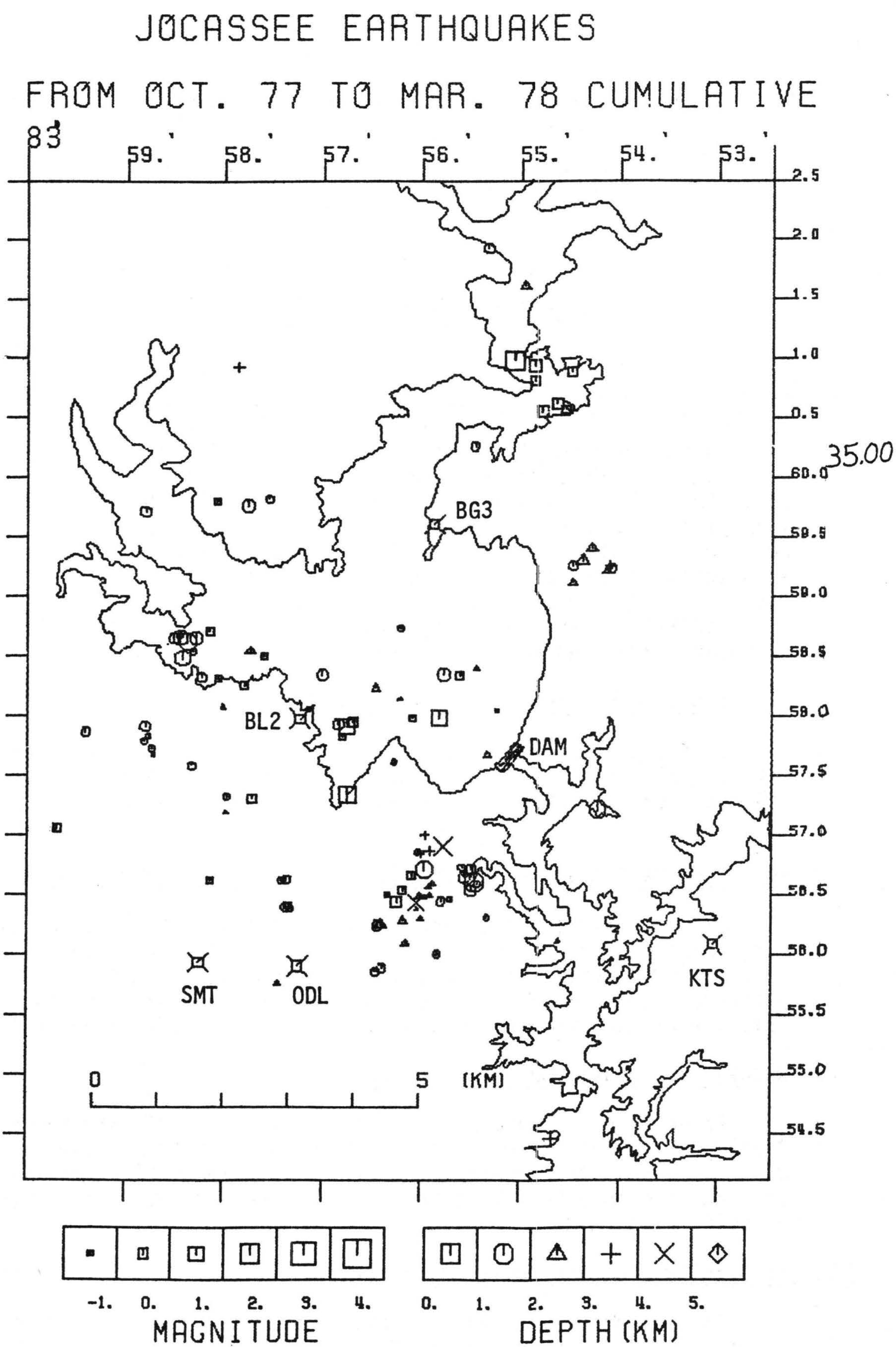

JØCASSEE EARTHQUAKES
FRØM ØCT. 77 TØ MAR. 78 CUMULATIVE
83
59.
58.
57.
56.
55.
54.
53.
2.5
2.0
1.5
1.0
0.5
60.0
35.00
59.5
59.0
58.5
58.0
57.5
57.0
56.5
56.0
55.5
55.0
54.5
BG3
BL2
DAM
SMT
ODL
KTS
0
5 (KM)
-1.
0.
1.
2.
3.
4.
MAGNITUDE
0.
1.
2.
3.
4.
5.
DEPTH (KM)

Figure 1

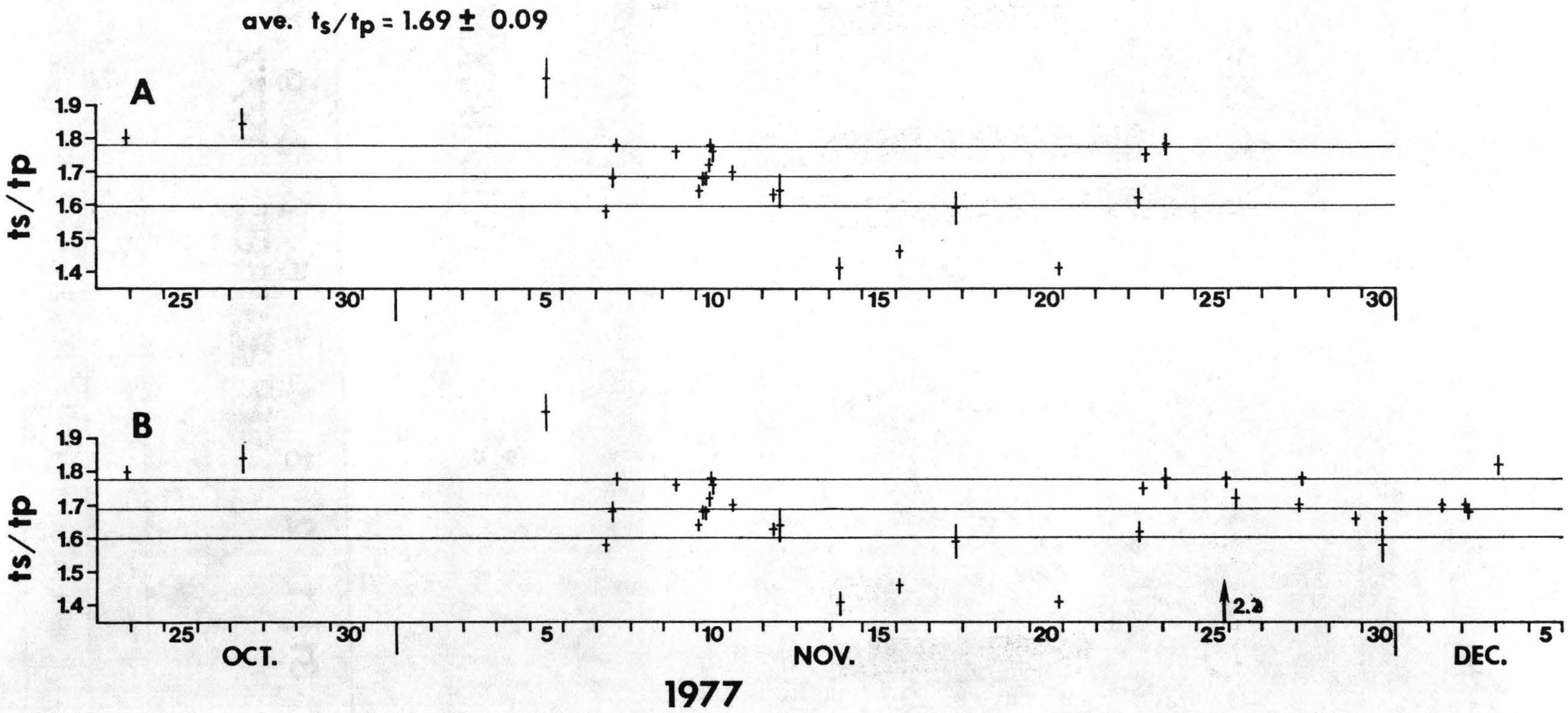
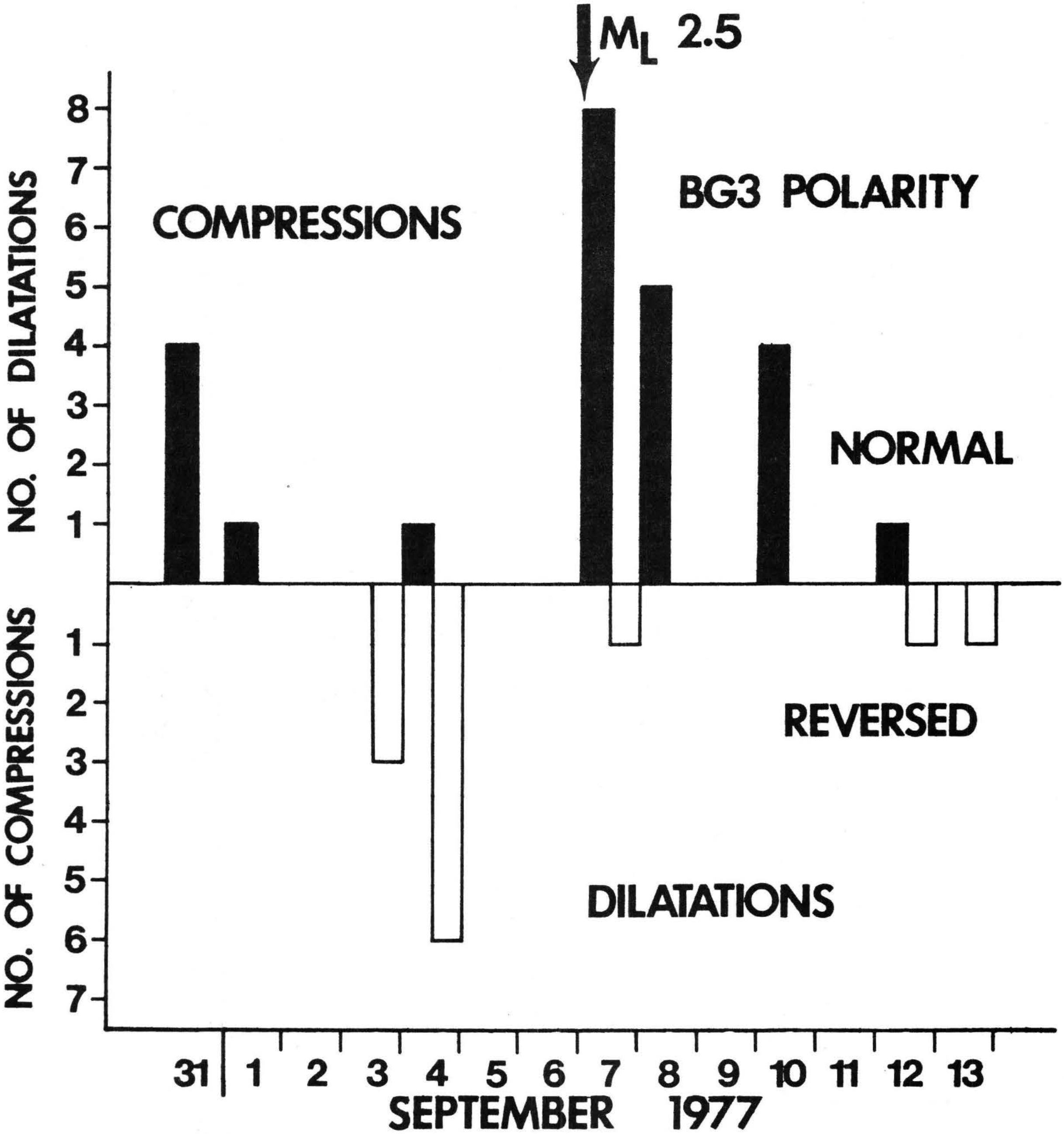

ave. $t_s/t_p = 1.69 \pm 0.09$
A
B
ts/tp
1.9
1.8
1.7
1.6
1.5
1.4
25
30
5
10
15
20
25
30
5
2.3
OCT.
NOV.
DEC.
1977

Figure 2



M_L 2.5
NO. OF DILATATIONS
8
7
6
5
4
3
2
1
COMPRESSIONS
BG3 POLARITY
NORMAL
NO. OF COMPRESSIONS
1
2
3
4
5
6
7
REVERSED
DILATATIONS
31
1
2
3
4
5
6
7
8
9
10
11
12
13
SEPTEMBER 1977

Figure 3

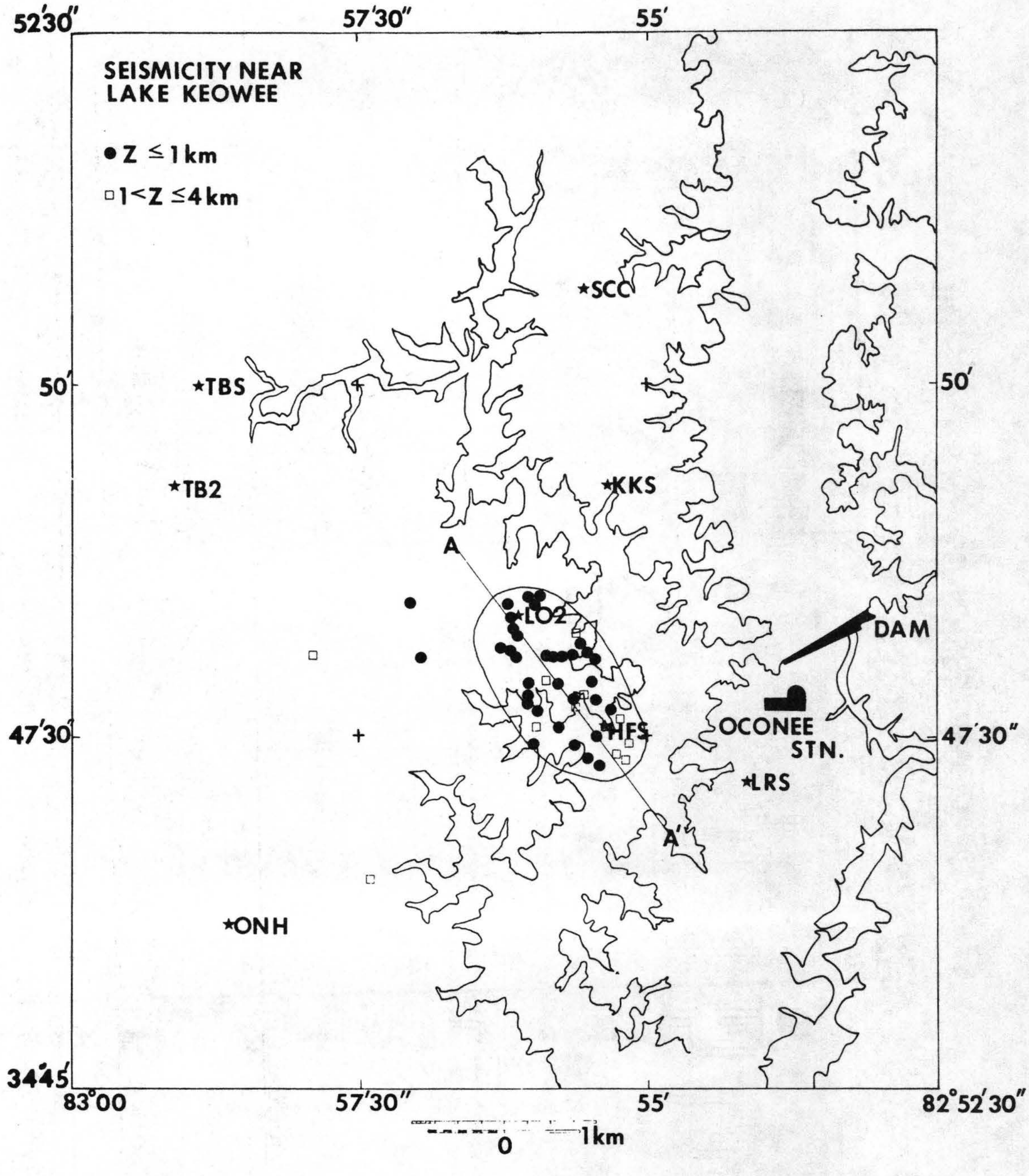

SEISMICITY NEAR LAKE KEOWEE
Z ≤ 1 km
1 < Z ≤ 4 km
52'30"
57'30"
55'
50'
47'30"
34°45'
83°00
82°52'30"
SCC
TBS
TB2
KKS
A
A'
LO2
HFS
DAM
OCONEE STN.
LRS
ONH
0
1km

Figure 4

SEISMIC ACTIVITY ASSOCIATED WITH IMPOUNDMENT OF MONTICELLO RESERVOIR

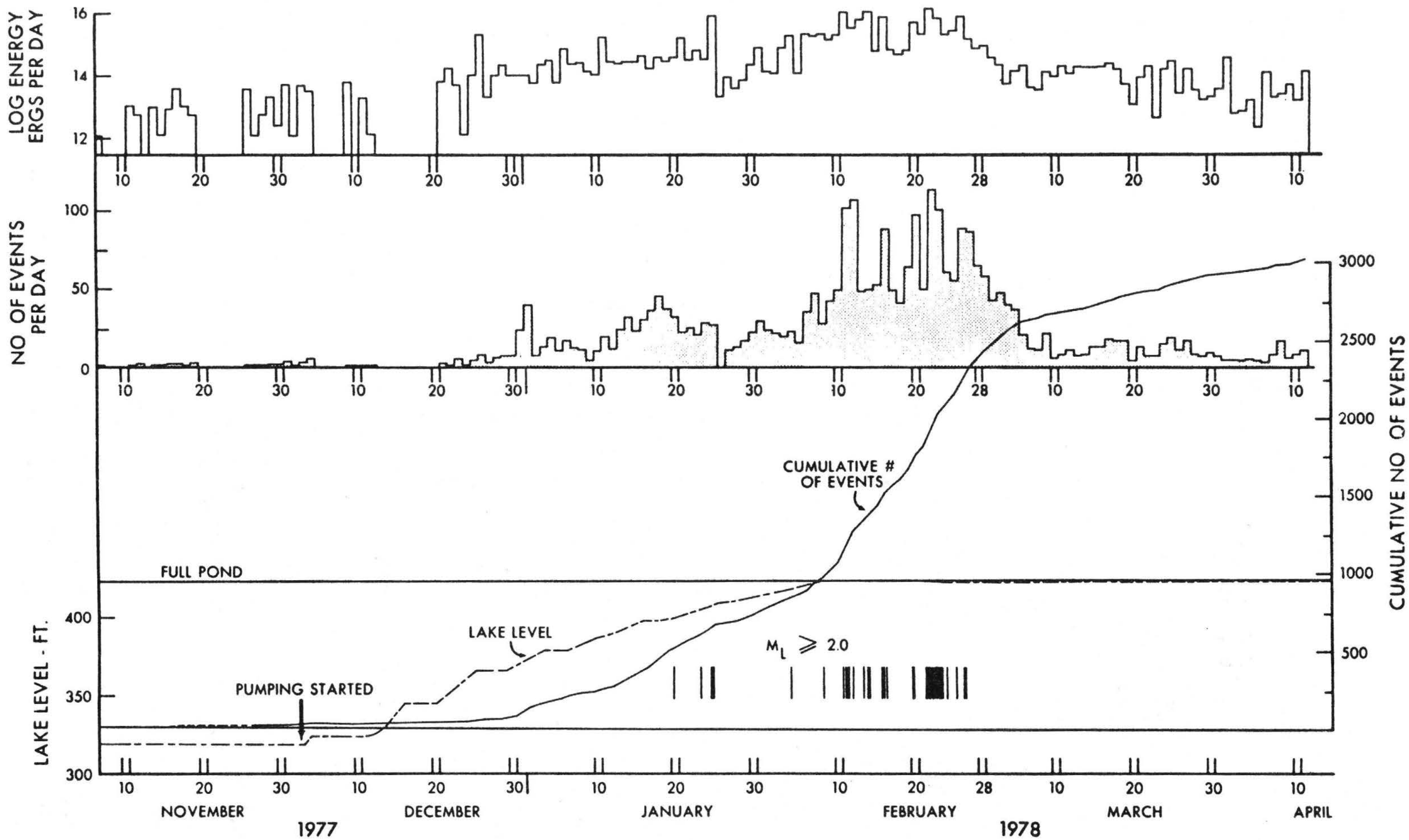


Figure 5

P.B.1.

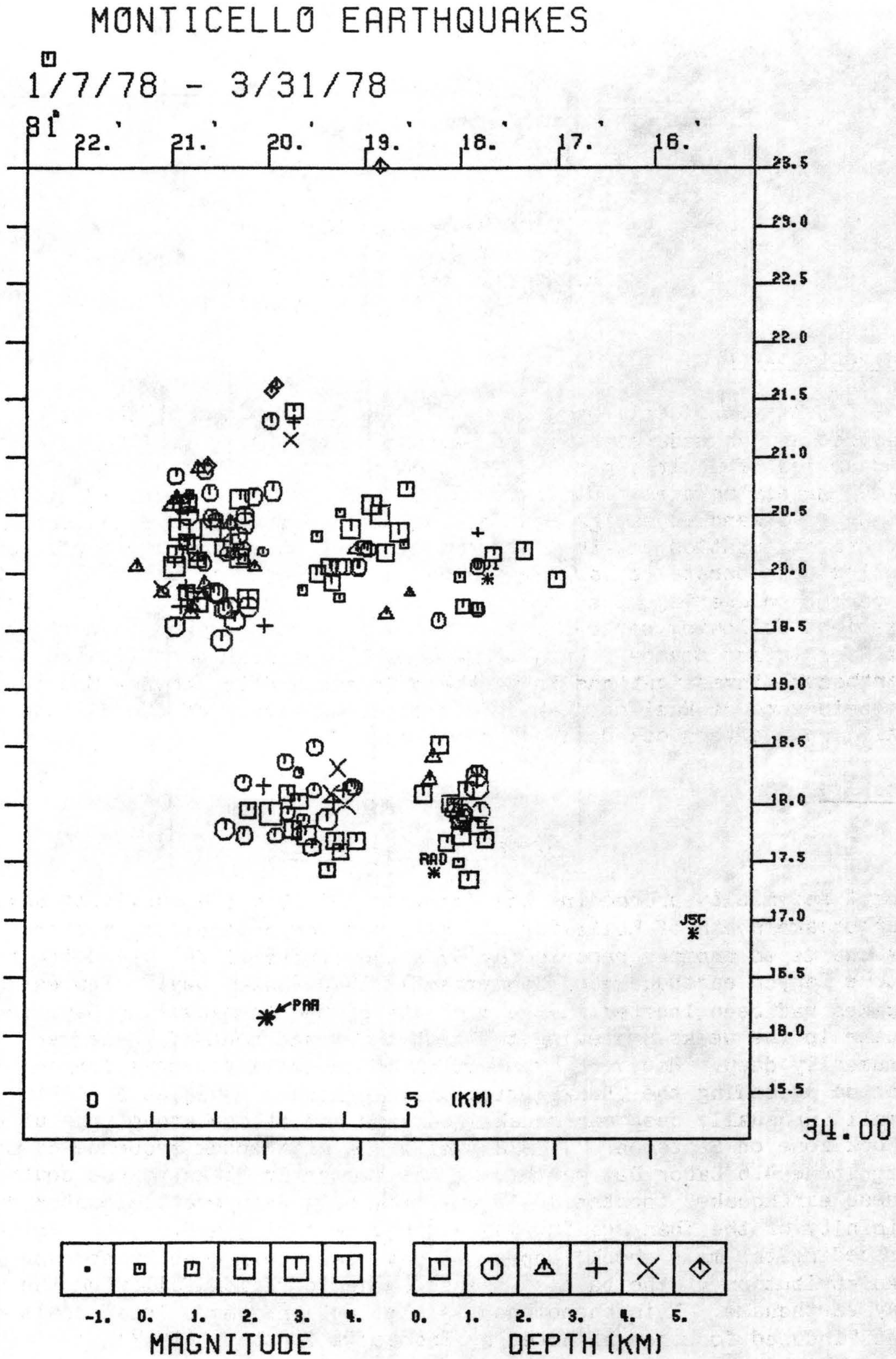

MONTICELLO EARTHQUAKES
1/7/78 - 3/31/78
81
22.
21.
20.
19.
18.
17.
16.
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
15.5
RAD
JSC
PAR
0
5
(KM)
34.00
-1.
0.
1.
2.
3.
4.
MAGNITUDE
0.
1.
2.
3.
4.
5.
DEPTH (KM)

Figure 6

Seismic Studies for Earthquake Prediction

8-9930-01727

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Investigations

The objectives of this project are to develop, by seismological techniques, an understanding of earthquake mechanics and the physical properties of fault zones leading to the prediction of potentially damaging earthquakes. During the reporting period project effort was directed toward investigations of spatial and temporal variation in stress orientation and the redistribution of stress on a regional scale following moderate to large earthquakes. Sympathetic seismicity - the apparent triggering of events well outside the aftershock area - has been examined following several moderate-to-large earthquakes in northern California and Nevada. Project personnel have also participated in earthquake investigations in northern Greece and in the New Madrid seismic zone at Reelfoot Lake, Tennessee. Analysis of the Willits, California aftershock data has continued.

Results

Sympathetic Seismicity

Local seismicity proceeding the November 28, 1974 (Thanksgiving Day) earthquake north of Hollister was examined for premonitory patterns such as the depth anomaly reported by Bufe and others (1974) preceding the Stone Canyon earthquake of September 4, 1972 (Labor Day). Few earthquakes had been located in the vicinity of the Thanksgiving Day earthquake in the weeks preceding the main shock and none of these were unusually deep. However, examination of seismicity over a longer time period preceding the Thanksgiving Day earthquake revealed a cluster of small, unusually deep earthquakes beneath and at one end of the aftershock zone on September 7, 1972, while the aftershock sequence of the magnitude 4.6 Labor Day earthquake was occurring 36 km to the south. These earthquakes (depths 10-15 km), the only deep events located in the vicinity of the Thanksgiving Day earthquake during a 4.5 year period preceding the main shock, appear to have been triggered by stress redistribution at the base of the seismogenic region following the Labor Day earthquake. This phenomenon is similar, on a more local scale, to the "induced foreshocks" noted by Fedotov and others (1977).

As part of our program to identify likely sites of future earthquakes we have examined regional seismicity following moderate earthquakes in central California. The most probable cases (3) of triggered events involve small, relatively deep earthquakes along the coastal Hosgri and Naciemento fault zones following (within 3 days) moderate ($M \geq 4.6$) earthquakes on or northeast of the creeping section of the San Andreas fault (Figure 1). This sympathetic seismicity along subparallel faults separated by 70 km or more is reminiscent of the apparently aseismic sympathetic surface faulting reported on the San Andreas fault following the Borrego Mountain earthquake (Allen, and others, 1972).

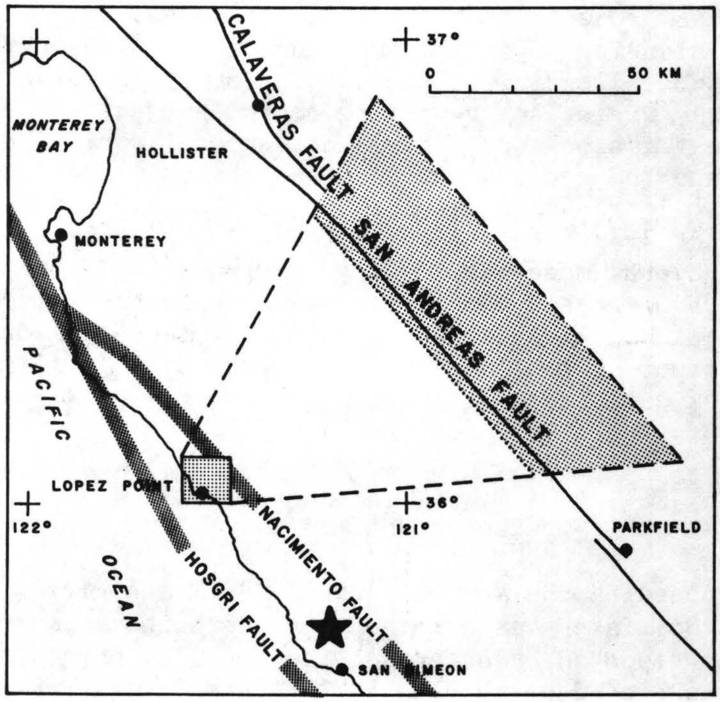

Figure 1. Geometry of sympathetic seismicity (triggered foreshocks?) at Lopez Point, California. Lopez Point earthquakes (in 10 km square) at depths below 10 km follow, within 3 days, larger ($M \geq 4.6$) earthquakes in the shaded sector along the San Andreas fault but do not follow earthquakes near Parkfield or Hollister. The star near San Simeon is the epicenter of the magnitude 6 earthquake of November 22, 1952, which probably occurred on the same fault system as the Lopez Point events. This earthquake is the largest to occur in central California since 1934.

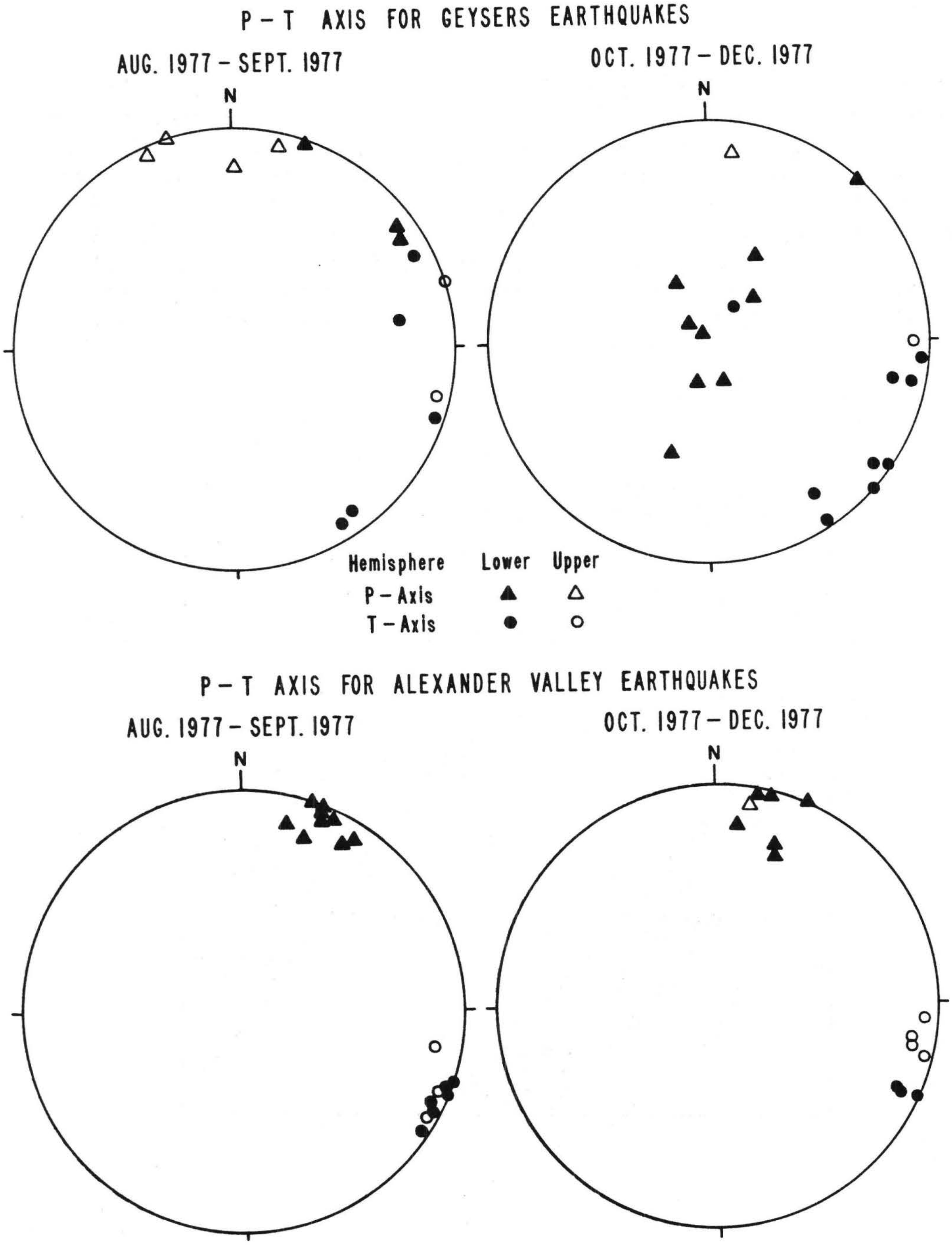

Figure 2. Temporal changes in stress orientation from focal plane solutions in The Geysers region, northern California. a.(top) Inferred maximum (P) and minimum (T) principal stress orientations from earthquakes in or near the steam production zone at The Geysers preceding and following the September 22, 1978 (M = 3.7) earthquake. The September 22 earthquake was strike-slip. b.(bottom) Inferred stress orientations from earthquakes along the Maacama fault at Alexander Valley, 10 km south of The Geysers, during the same time periods as above.

Stress Orientation

Large temporal changes in focal plane mechanisms of earthquakes at The Geysers have been documented (see Figure 2a). In August-September 1977 and during the previous two years the predominant mode of faulting at The Geysers was strike slip. This was true throughout the range of focal depths (0-5 km) of Geysers earthquakes. Since the end of September, 1977, the dominant mechanism has been normal faulting. This change in stress orientation followed the occurrence on September 22 of a magnitude 3.7 strike-slip event, the largest earthquake to be located at The Geysers to date. The change can be explained as a reduction in northeasterly compression such that the vertical (lithostatic) compression, which was the intermediate stress, is now the principal compression. This interpretation is supported by the observation that very shallow (depth less than 2 km) earthquakes at The Geysers continue to be strike slip. The majority of earthquakes are deeper (2 to 4 km) and have focal mechanisms indicating normal faulting. The reduction (approximately 500 bars) in northeasterly compression may be a local response to the September 22 earthquake, since strike-slip faulting continues to predominate (see Figure 2b) along the Maacama fault 10 km south of The Geysers. However, some regional reduction in cross-fault compression may be inferred from the greatly increased level of earthquake activity in the surrounding region which began with a swarm at Alexander Valley in September 1977. In addition to moderate earthquakes along the Maacama system at Ukiah and Willits, a very unusual sequence of earthquakes occurred near the San Andreas fault at Fort Ross (Stickney, 1978). The Geysers, because of instabilities resulting from fluid withdrawal and injection or perhaps inherent in a steam reservoir, may be a "tectonic barometer", more sensitive to stress changes than the surrounding region.

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Teleseismic Search for Earthquake Precursors

8-9920-02142

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Investigations

1. To test whether the present global seismograph network is capable of detecting unusual patterns of seismicity precursory to major earthquakes by studying regional seismicity prior to recent major earthquakes in Peru and in the Aleutians.

2. To use relocated hypocenters to test whether moderate and large subduction zone earthquakes tend to nucleate in the same small regions of the subduction zone and whether the improved hypocenters of moderate earthquakes permit better definition of smaller tectonic blocks within the subduction zone.

3. To determine the effect, on the seismicity of an incipient source region, of a major earthquake occurring nearby, and to interpret the presence or absence of such seismicity in terms of models of the preparation of source regions for major earthquakes.

Results

Jim Dewey and Bill Spence have completed relocation of over 500 teleseismically-recorded earthquakes from the region of coastal Peru between 8^{o}S and 14^{o}S for the interval 1964 through 1977. The following conclusions emerge from research of the last half year:

1. The principal seismic source region of the Peruvian subduction zone, occurring from 60 km to 200 km landward of the Peru trench, consists of two zones of earthquakes. The interface thrust (IT) zone, consisting of shocks occurring in the interface between the Nazca and South American plates, includes the major (fault length greater than 100 km) earthquakes of October 1966 and October 1974. The coastal region intraplate (CRI) zone, consisting of earthquakes occurring within the plates, includes the major earthquake of May 1970.

   Corallary 1-A: Within any longitudinal section of the Peruvian subduction zone, there may be effectively two seismic "gaps", one corresponding to the IT zone and one corresponding to the CRI zone. It is not clear that the occurrence of a major earthquake in one zone lessens the danger of a major earthquake from the other zone.

Corollary 1-B: The presence of two nearby seismic zones, each perhaps caused by very different stress regimes, may complicate the job of detecting unusual seismic activity precursory to a great earthquake in one of the two zones, since such precursory activity could be masked by activity occurring in the other zone.

2. In the region of offshore Peru, it appears possible to teleseismically separate the IT zone from the CRI zone. When looking at a section transverse to the strike of the subduction zone, earthquakes thought, on independent evidence, to be occurring on the plate interface occur in a zone spatially separated from the zone in which lie earthquakes thought, on independent evidence, to be occurring within the Nazca plate.

Corollary 2-A: In searching for unusual activity that might be precursory to a large earthquake in either zone, it may be possible on the basis of location alone to consider earthquakes from each zone separately, rather than being forced to search for precursory activity from within two intermixed families of earthquakes.

Caveat 2-A: The region of central Peru may be a rather atypical subduction zone. It is possible that the CRI zone does not exist in some subduction zones or, if it does, that it cannot be resolved from the IT zone with teleseismic data. In the latter case, focal mechanism studies would be necessary to distinguish IT earthquakes from CRI earthquakes.

3. Separation of CRI zone earthquakes from IT zone earthquakes brings into prominence a group of moderate earthquakes occurring in the hypocentral region of the October 1974 earthquake in the five years preceding the main shock. These earthquakes are the only well-located earthquakes occurring in the 650 km long segment of the IT zone studied that were not part of the mainshock-aftershock sequences of the earthquakes of October 1966 and October 1974.

Corollary 3-A: These shocks may be the type of precursory seismicity we are looking for to help predict great subduction zone earthquakes.

Caveat 3-A: Until we have relocated pre-1964 shocks, we cannot be sure how unusual, in a temporal sense, these shocks are. For example, the hypocentral region of the October 1974 earthquake could be a region of the IT zone which is particularly favorable for the nucleation of all sizes of earthquakes.

4. In the month following each of the major shocks of October 1966, May 1970, and October 1974, there were no well-located teleseismically-recorded shocks from the other two source regions. The stress changes associated with each of the main shocks was insufficient to immediately trigger an earthquake in the other two source regions. This negative result is of interest because, for example, by the time of the 1966 earthquake, the source regions of the 1970 and 1974 earthquakes were also approaching the end in time of the strain cycles that were to result in their respective earthquakes. Evidently, however, no part

of the 1970 or 1974 source regions was sufficiently near the point of rupture to produce (within one month) a teleseismically-recorded earthquake as a result of triggering by the October 1966 shock.

Reports

Dewey, J. W. and Spence, W., 1978. "Seismic Gaps in Goastal Peru," to be published in the Procedings of the Conference on Defining Soon-to-Break Seismic Gaps, Convened Under Auspices of National Earthquake Hazards Reduction Program (U.S.G.S. Open-File Report).

Seismicity and Seismic Velocity Studies and Crustal Structure in Southern California

Final Technical Report
U.S. Geological Survey Contract No. 14-08-0001-16711
1 October 1977 to 30 September 1978

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SUMMARY

The U. S. Geological Survey Contract No. 14-08-0001-16711 was awarded in response to the proposal by the California Institute of Technology which was divided into four separate efforts. The results are summarized below.

1. P-velocity Change (quarry blasts)

No changes in P velocity exceeding 2% have been observed along any paths in southern California during the contract period. However, there was no earthquake $M_L \geq 5.2$ in southern California during the same period; the question of whether a detectable premonitory change occurs or not before a large earthquake remains unresolved.

One notable long-term change is seen for the Corona to Riverside path. For this path, a very long baseline has been established by Gutenberg's data together with the data obtained under this contract. Although the data since 1973 show little change, the change over a much longer time period from 1950 to 1978 seems to correlate with the two major tectonic events in southern California, the southern California uplift and the 1971 San Fernando earthquake. Although no definitive conclusion can be drawn from this single set of data, the result suggests an importance of establishing a long baseline of precise velocity measurements in a tectonically active area. Figure 1 shows the results for the Mojave, Victorville, Gypsum Canyon, and Corona blasts.

2. Microearthquake Survey

Numerous small earthquakes occurring as 'swarm' type activity began in the Palmdale area, California, in November 1976. During the period 1 October 1977 through 30 September 1978 Caltech continued monitoring this anomalous seismicity increase using movable seismographic trailers. All located events in the Palmdale area from 11/3/76 - 10/2/78 are shown in Figure 2. The data are complete above M = 0.5 through June 1978. The data from July - October 1978 are probably incomplete.

From 3 August to 1 October 1978 we operated four seismographic trailers in the Cajon Pass area to study the detailed seismicity patterns south of the Palmdale activity described above. Presently we are developing film recordings and reducing the data for this survey.

3. Regional Seismicity

Analysis of seismicity data before the 1971 San Fernando earthquake revealed a relatively quiet period before the main shock. This period was followed by a tight clustering of activity near the main-shock epicenter immediately before the main shock. Use of this seismicity pattern together with changes in the wave forms and spectra appears useful for detecting stress concentration near the main-shock epicentral area.

4. Crustal Structure

The compressional velocity within the upper mantle beneath southern California is investigated through observations of the dependence of teleseismic P-delays at all stations of the array on the distance and azimuth to the event. The variation of residuals with azimuth was found to be as large as 1.3 sec at a single station; the delays were stable as a function of time, and no evidence was found for temporal velocity variations related to seismic activity in the area. These delays were used in the construction of models for the upper mantle P-velocity structure to depths of 150 km, both by ray tracing and inversion techniques. The models exhibit considerable lateral heterogeneity including a region of low velocity beneath the Imperial Valley, and regions of increased velocity beneath the Sierra Nevada and much of the Transverse Ranges. These ranges are attributed to variation in the degree of partial melting within the upper mantle.

Through the inversion of Rayleigh wave dispersion data obtained from the analysis of teleseismic surface waves recorded across southern California, we have obtained average S-wave models for the southern Mojave-central Transverse Ranges and the Peninsular Ranges. The observed P-wave velocities and the calculated Poisson's ratio from both P- and S-wave data require a quartz rich crust for the Mojave and a more mafic crust for the Peninsular Ranges. All S-wave models suggest a slight mid-crustal velocity reversal that is approximately coincident with the bottom of the seismic zone.

We have designed a versatile digital seismographic recording system. The system is built around a computer and is quite versatile as the characteristics are modified by simply changing the computer program.

The individual seismic units (6) are based on the Intersil 6100 micro-processor, and represent an extension of a system developed for the USGS for the collection and transmission of geophysical data over voice grade dial-up telephone lines. The system is modular and has a bus structure that allows the user to decide which boards are applicable for their needs.

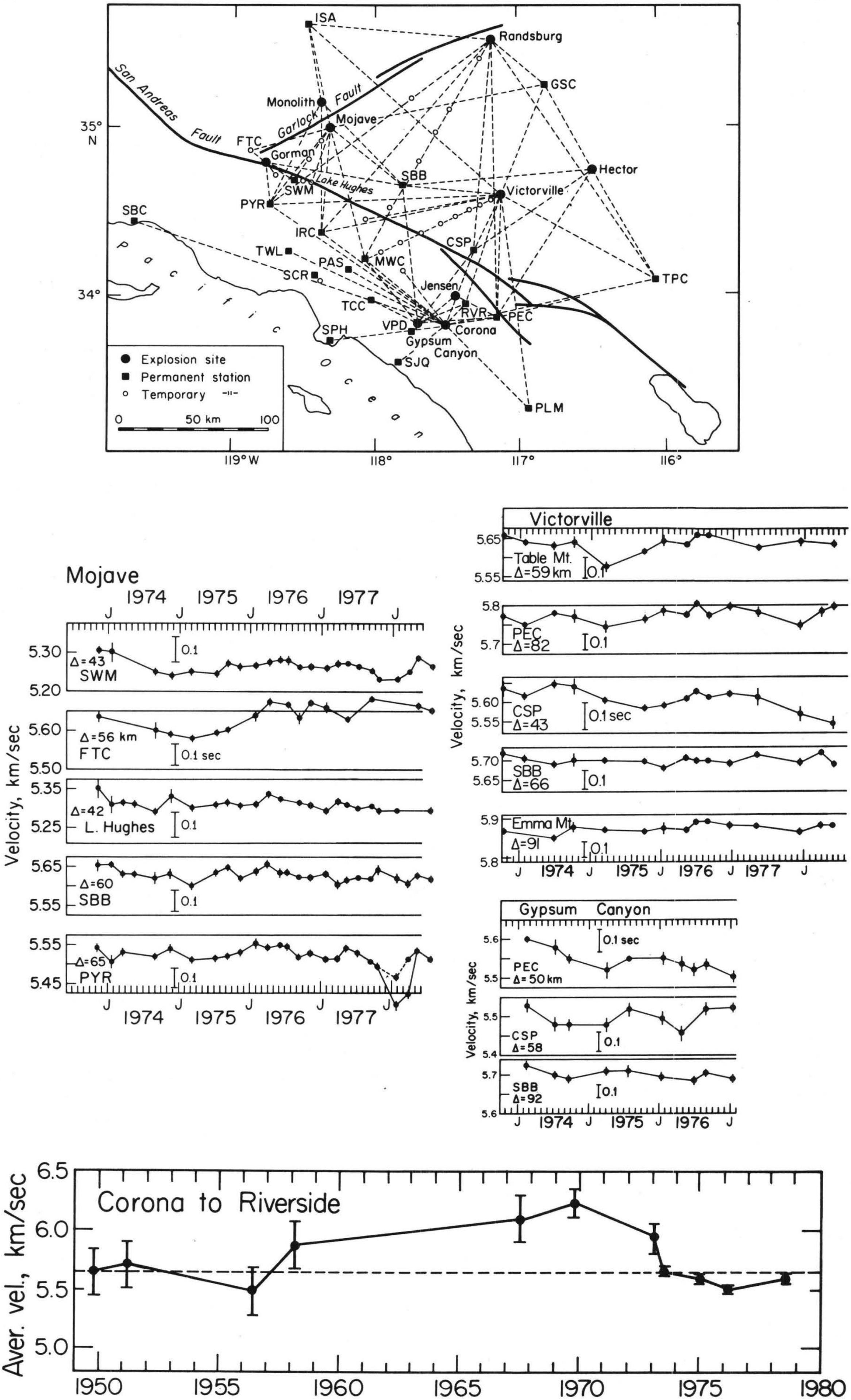

Figure 1. Temporal Velocity Change in Southern California

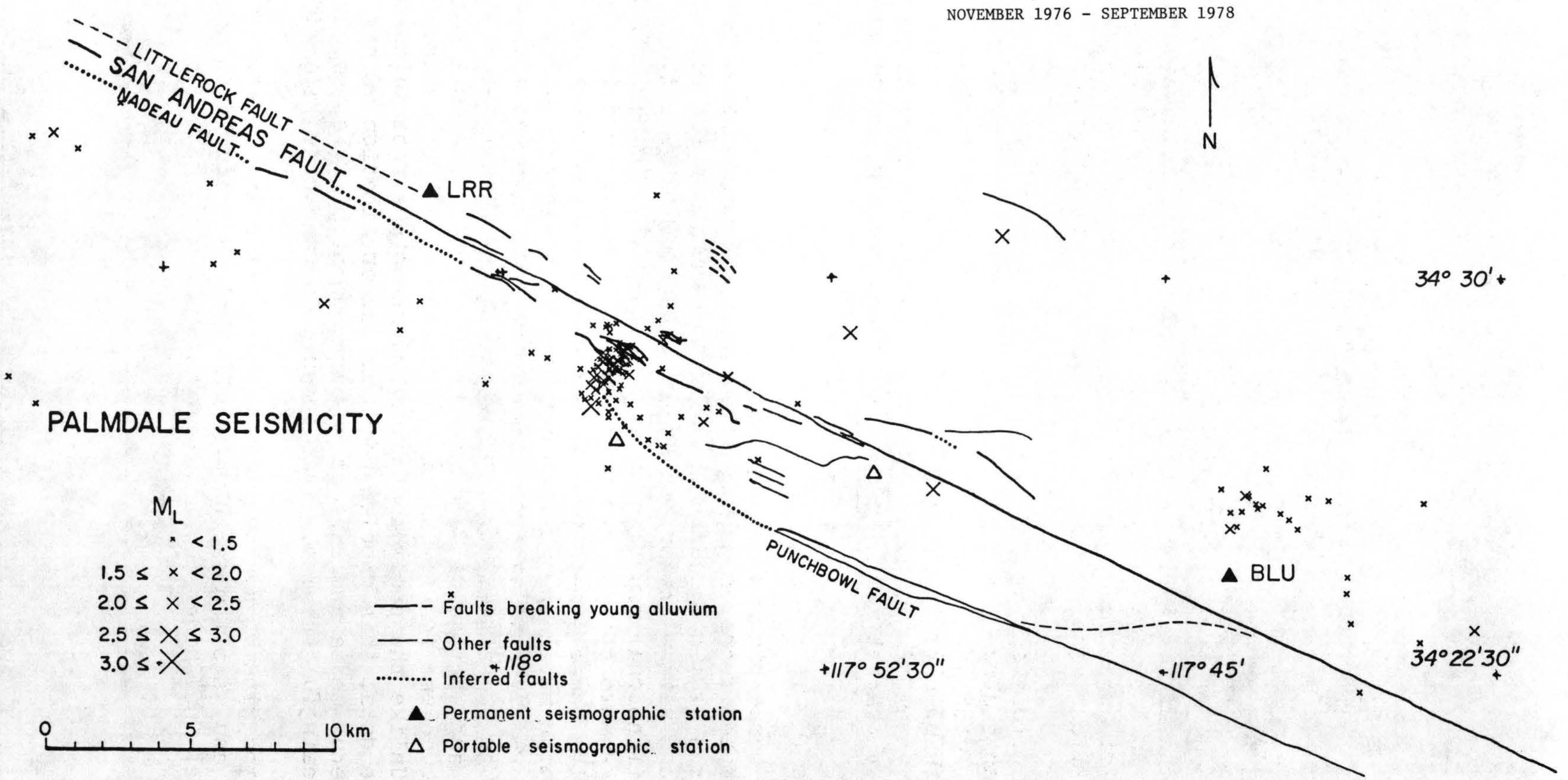

Figure 2. Microearthquake Activity in the Palmdale Area

Microearthquakes Data Analysis

8-9930-01173

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Investigations

The primary focus of this project is the development of state-of-the-art computation methods for analysis of data from microearthquake networks. Our ultimate goal is the application of these methods to earthquake data to 1) detect seismic precursory phenomena useful for earthquake prediction, and 2) relate seismicity and earth structure to geologic processes.

Our principal effort during the past year has been to address the problem of determining earth structure from surface array observations of body wave traveltimes. To this end, several families of computer programs have been developed to trace rays in three-dimensional velocity structures, and to solve a linearized system of equations relating traveltime observations to unknown parameters that characterize the velocity structure and source coordinates.

Results

To date, four basic programs have emerged:

(1) A generalized inversion package that will solve the over-determined system of equations $Ax = b$ by singular value decomposition for very large systems of equations without resort to normal equations ($A^tAx = A^tb$).

(2) A three-dimensional ray tracing package that will trace a minimum time path between two points, and compute the traveltime and its derivatives.

(3) An iterative three-dimensional modeling program employing ray tracing in heterogeneous media that determines lateral velocity heterogeneities beneath a receiver array from teleseismic body-wave traveltimes.

(4) A program to iteratively determine both three-dimensional velocity structure and earthquake focal parameters when the seismic sources lie within the volume for which information on velocity heterogeneity is sought. Unlike the problem of modeling structure from teleseismic traveltime data, this problem requires the application of ray tracing in heterogeneous media and interative improvement of trial solutions to provide meaingful results. This program is currently under development.

In collaboration with D. R. Brillinger, a statistician, we have developed a point process analysis for earthquake data that is incomplete, and applied it to the study of the Chinese earthquake history.

In collaboration with R. S. Yeats and R. F. Yerkes, geologists, we have completed three papers relating seismology and geology in the western Transverse Ranges. Completion of these synthesis papers allowed us to quickly analyze and complete a preliminary report on the recent Santa Barbara earthquake and its major aftershocks within one month after it occurred.

Reports

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Parkfield Prediction Program

8-9930-02098

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Goals

The principal goal of this project is to predict in advance the next magnitude six (or larger) Parkfield earthquake. The recurrence interval suggests that the chances are better than 50-50 that such an event will occur in the next ten years. Ten years would thus be a nominal estimate for the life of the project. A long-term goal will be to understand the role of the en echelon offset in the SA which spans the Cholame Valley just south of Gold Hill. The foreshocks and epicenter of the 1857 earthquake were located in this vicinity, and by analogy with the Anatolian Fault, may have been located at this offset. I have argued that the 1966 rupture terminated at this point (Lindh and Boore, 1973). Thus any understanding gained concerning the relation of this major discontinuity to the local strain and seismic regime might also pertain to the fundamental question of how great earthquakes like 1857 nucleate, and what relation this process has to that for events of magnitude six or seven.

More immediate short-term goals are:
1) To use existing geodetic and creep data to define as precisely as possible the slip distribution on the SA in the Parkfield area. Using linear inverse theory we will then attempt to design a program of observations to better resolve the slip distribution in time and space (along the fault and with depth) if this appears possible. One additional set of observations that will be undertaken immediately are a few new alignment arrays to fill gaps in our knowledge of the surface slip regime (possible locations are indicated by capital A's in Figure 1). An important question that will have to be faced is whether dislocations in an elastic half-space are an appropriate model, and if not, whether computable alternatives exist. This question is central to the interpretation of point strain measurements, such as those from strain and tilt meters.

2) To adapt the crustal model used by Jerry Eaton in 1966 to the present stations configuration, and to use this to relocate the earthquakes in the Parkfield area since 1969. We will try to fill the gap in '67-'68, between the 1966 aftershock studies and the USGS catalog that begins in

1969. We will also estimate the magnitude threshold to which the catalog is essentially complete, and fill any minor holes that exist. The revised catalog will then be used to compare the seismicity pattern along the fault to the 1966 aftershock pattern, as well as to the slip function obtained in 1). In addition, it will be used to study the time history of such gross characteristics as mean depth, B-slope, clustering in space and time, and spatial migration of hypocenters.

3) The amplitude ratio/focal mechanism study we attempted to initiate this year will be pursued in the Parkfield area (see last year's proposal), along with the zero crossing/stress drop work we tried on the Oroville foreshocks (see semi-annual report). By coordinating our efforts with Bill Bakun's detailed studies of individual events, we hope to quantify what relation, if any, the simple measurements we made at Oroville (P/S amplitude ratios, zero-crossing times and coda lengths) have to source orientation, moment, and duration. In particular, we will look for gradual changes in stress drop and source orientation that might reflect stress accumulation and/or fault zone property changes. As the foreshocks and main events of the last two Parkfield magnitude six events located at approximately the same point (the star in Figure 1 near the north end of the 1966 break) and as microseismicity continues at that point, it seems an ideal place to study the time history of such source characteristics. As the data accumulates it will also provide an opportunity to study the frequency of short term fluctuations in these characteristics. Such short term fluctuations might be useful in identifying immediate foreshocks to a large event, if and when they happen.

The strategy the first year will be to undertake an integrated analysis of the geodetic, creep and seismic data collected for the last ten years and of the strain, tilt and magnetic measurements made by the USGS and CIT in the last few years.

Instruments currently operating in the area are shown in Figure 1, along with the geodetic lines along which yearly measurements are made.

Assuming that the creep data constrain the very shallow slip, we will use Wayne Thatcher's geodetic inversion program to determine how well the results from the geodometer net constrain the slip distribution at depth (2? to 10 km) and whether any further measurements would add significant information in a few years.

A parallel modeling effort will be undertaken with Bill Stuart and Ralph Archuleta, using their 3-D finite-element fault simulation program to model the slip function obtained above with a frictional strength distribution that varies on the fault surface. In particular we will be interested in seeing whether the stronger (or stuck) patches occur at the ends of the 1966 break, near where much of the subsequent micro-seismicity has located.

A second use of the program will be to predict on the basis of Bill's strain-softening/instability model what premonitory deformation would be expected, for a given strength distribution, before the next Parkfield earthquake. The magnitude of these deformations may allow us to assess the adequacy of the observations being made in the area, and hopefully will be of use in sharpening the observational half of the experiment.

The goal is to arrive at an experimental design that will allow us, when the next large earthquake occurs, to distinguish between Bill's instability model, which requires extensive premonitory slip, and the null hypothesis, that an earthquake is just an Heaviside function in time. (We will also consider, of course, any other quantitative models that are proposed.) As the problem is dreadfully non-linear, this will of necessity be an iterative process; our hope is that feed-back loops can be estabilished between the theoretical models and the observational program so that there is some chance of reaching demonstrable conclusions with the expenditure of a finite amount of time, toil and money.

Another important strategic consideration will be to reconcile tidal precision point measurements of tilt and strain, which do not appear to have the long term stability required to measure secular strains, with the very stable geodetic measurements, which are repeated so infrequently as to be of no use in detecting short-term premonitory deformation. The two-color laser would be the slick way out of this problem. It will be a great boon to this project if Parkfield is chosen as the site for one of the new instruments.

Another approach we will try is to tie as many as possible of the point measurements together with short level lines and to expand of the small HP-3800 nets like those Mike Lisowski already has in the Parkfield area. This will allow a direct correction to be made for large non-tectonic drifts, and may also provide a test of the idea that large strains are occurring in and immediately adjacent to the fault zone.

A third approach will be to carefully examine the large quantity of tilt and strain data collected the last year or two by the USGS and Caltech in the Gold Hill area for internal consistency (Figure 1). In addition, three Sachs-Everson down-hole volumetric strain-meters will be installed in the Parkfield area. Each of these sites will also have a shallow 3-component invar wire strain-meter and a small geodetic figure for comparison. It may be however, that the long-term stability question will remain a sticking point and we will eventually be driven to more exotic hardware, like for instance, long-baseline tilt and strain-meters.

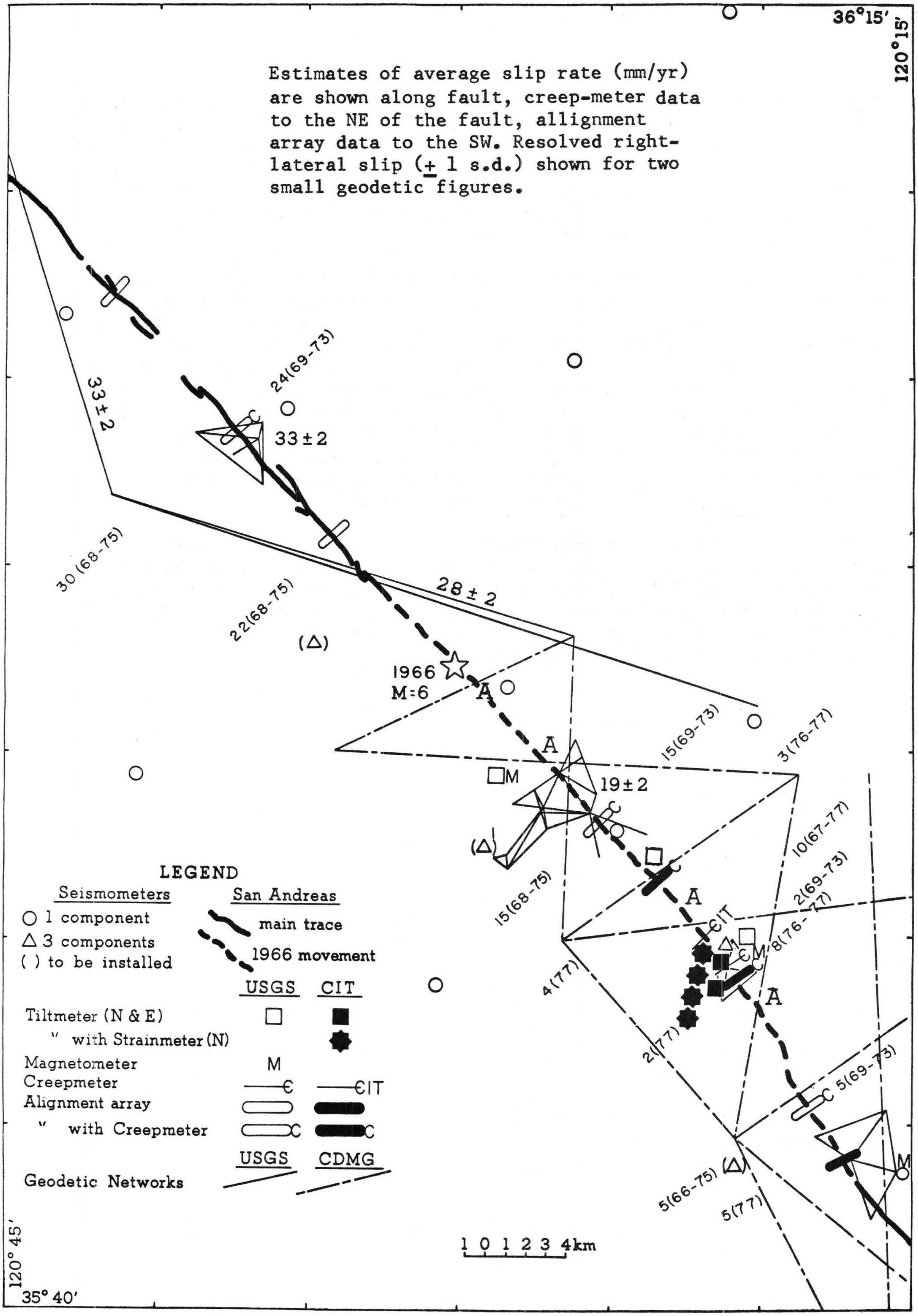
Invesitgations

The Parkfield area has been the site of four very similar magnitude six earthquakes in this century. The last three have had similar moments ($\sim 10^{26}$ dyne/cm), and have involved ground breakage along the same section of the San Andreas (SA), along the northeast edge of the Cholame

Valley. At least the last two have had foreshock activity, including one magnitude five foreshock in the final minutes before each main event. In addition the transition from creeping to locked sections of the SA occurs in the Parkfield area, apparently without the complications of slip on subsidiary strands. The northern terminus of the 1857 earthquake is in this area, and it appears to have been the site of several foreshocks and the main epicenter as well (Sieh, 1979).

Surface creep and geodetic measurements make it clear that strain is accumulating along this stretch of the SA, and suggest that the strain gradients are high, both in time and space. We are now past the minimum interval between magnitude six's is this century. As the zone that broke in 1966 has been the site of continuing microseismicity up to the present (including a cluster of activity near the 1966 epicenter), and is already the site of a large number and variety of other measurements, this region seems to us emminently suitable for a detailed prediction experiment. This conclusion is further strengthened by the existence of qualitative evidence that the 1966 event was preceded by accelerating aseismic deformation in the weeks prior to the main event.

We have initiated such an experiment in the Parkfield area. Our intention is that by emphasizing analysis of existing data and by close co-operation with Bill Stuart's modeling efforts, it will be possible to pose answerable questions concerning the slip and/or stress distribution at Parkfield. These questions will then be used to better focus a program of augmented field observations.


36°15'
120°15'
Estimates of average slip rate (mm/yr) are shown along fault, creep-meter data to the NE of the fault, allignment array data to the SW. Resolved right-lateral slip (± 1 s.d.) shown for two small geodetic figures.
33±2
24(69-73)
33±2
30(68-75)
22(68-75)
28±2
(Δ)
1966
M=6
A
A
15(69-73)
3(76-77)
M
19±2
(Δ)
10(67-77)
A
15(68-75)
2(69-73)
8(76-77)
CIT
M
A
4(77)
2(77)
5(69-73)
5(66-75)
(Δ)
5(77)
M
LEGEND
Seismometers
○ 1 component
Δ 3 components
( ) to be installed
San Andreas
main trace
1966 movement
USGS
CIT
Tiltmeter (N & E)
" with Strainmeter (N)
Magnetometer
M
Creepmeter
CIT
Alignment array
" with Creepmeter
USGS
CDMG
Geodetic Networks
1 0 1 2 3 4km
120° 45'
35° 40'

TECHNICAL REPORT SUMMARY

1 October 1977 to 31 March 1978

In-situ Seismic Wave Velocity Monitoring

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Continued monitoring through the past winter (when weather permitted) has confirmed that spurious travel-time variations, both long-term and short-term, are severely limiting the precision of our measurements, and are perhaps masking events of real interest, namely velocity variations due to stress changes at depth.

Long-term seasonal variations, which have been discussed in previous technical reports for the deep Bickmore Canyon monitoring and in the Event Summary, vol. 1, for all sites. occurred throughout the winter. Changes amounted to a slowing of about 0.2% of the travel-time or 18 msec for the 8-sec arrival at Bickmore Canyon, and about 1% for the first arrivals along both shallow paths at the winery site (9 msec on the N-S path and 5 msec on the E-W path). Variations are clearly rainfall related, substantiating our belief that they are caused by changes in water-table depth. However, the sense of the velocity change is opposite to what we would have expected, i.e., as the water table rose with increased rainfall, the travel-times increased at all sites, and are now decreasing again as the water-table drops.

We are experimenting with the use of down-hole geophones below our vibrator sites to compensate for very-near-surface changes, both by simply monitoring down-hole times, and by using the down-hole signal as the reference signal in cross-correlation.

The short-term variations observed since midsummer of last year are a scatter of about 5×10^{-4} of the travel-times measured at all sites during repeated runs made over a number of hours. This is an order of magnitude greater than that observed in the spring of 1977.

During the fall and winter, two sources of noise, transient electrical spikes on the geophone signal and 60 Hz noise on the correlated seismograms, increased markedly. The basic causes of each were discovered, and both were effectively eliminated. This improved data appearance, but did not reduce significantly the travel-time data scatter.

As part of these noise investigations, many parts of the vibrator and recording systems have been tested for stability and found to be functioning properly. The remaining candidates for the instability evidenced by the scatter are:

1. Vibrator reaction-mass instability due to improper feedback control.

2. Source spectrum variations, causing travel-time variations either due to geophone amplifier group delay variations with frequence, or to changing the interference pattern in the source pulse generated in the near-surface.

3. Telemetry transmitter radio and/or antenna problems, either direct variations, or possibly a complex interaction affecting the vibrator control system.

Contract #14-08-0001-16758

Some Characteristics of Foreshocks

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The main goals of this work are to establish characteristics of foreshocks on a time scale of hours, days or weeks (not long term seismicity), to evaluate their importance for earthquake prediction, and to understand how foreshocks relate to the preparation of a region before a large earthquake. The following paragraph summarizes the results thus far.

Foreshocks occur before a large fraction of the world's major ($M \geq 7.0$) earthquakes. In the general vicinity of the mainshocks (within 100 km) seismicity appears to increase to twice the previous level beginning about three months before the mainshock. A sharp increase in activity occurs within five days nearer the epicenter of the mainshocks, culminating in a final rapid acceleration of activity in the last day before them. A plot of the number of foreshocks per hour on the last day shows a continuing acceleration up to the time of the mainshocks, except for a decrease around six hours before them. The number of foreshocks per day is approximately proportional to the inverse of time before mainshock. This relationship is essentially unrelated to the magnitude of the mainshock. The magnitude of the largest foreshock is also unrelated to the magnitude of the mainshock. The ratio of the amplitudes of the P and S waves of each foreshock were found to be the same for foreshocks within each of three sequences studied, indicating that they may have similar faulting mechanisms. By assuming an inhomogeneous fault plane on which asperities fail by static fatigue, we derived an equation for accelerating premonitory fault slip as a function of time, which agrees with the observed time dependence of foreshocks.

We are pursuing this work now, seeking better ways to study the temporal and spatial variation of foreshocks, and their radiation patterns. We are also beginning an analysis of the long period radiation of selected earthquakes in order to establish that they are slow earthquakes and then to determine whether the slip accelerates from a slow particle velocity at the beginning or occurs more as after-slip. We are just now getting some simple programs working.

Reports:

Jones, L.M., and P. Molnar, Some Characteristics of Foreshocks, (submitted, Journal of Geophysical Research, March, 1978).

CONTINUOUS MONITORING OF SEISMIC TRAVEL TIMES NEAR THE SAN ANDREAS FAULT

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SUMMARY

The contract year 1977-78 was devoted to expanding the range and areal coverage of airgun produced seismic signals. The project fell into four phases, roughly achieved in each of the four contract quaters:

(1) acquisition and programming of a computer capable of controlling the airgun shot sequence, acquiring and processing telemetered travel time data, and storing the reduced results;

(2) installation of a 50 cfm electrically powered air compressor with 25 kW electric service lines; construction and deployment of a large airgun service raft; preliminary ranging with a loaned 2000 cubic inch airgun and consequent purchase of a 1000 cubic inch airgun firing chamber for the 1500C airgun on permanent loan to us; and installation of a telephone link from Bouquet Reservoir to the main telephone service line;

(3) construction of downhole instrumentation pressure chambers, power winch for raising and lowering instrument packages, and assembly of a complete set of FM telephone transmission modules (total of 16 pairs of modulation-demodulation units) with premliminary testing of all of the above;

(4) deployment, testing and systematic use of the above elements.

All elements of the research program are presently in hand. The three boreholes originally slated as targes for the airgun pulses are, with some telecommunications difficulty and delay, linked to Bougquet Reservoir. In addition, a fourth borehole at a range of 13 km has been brought on line. This hole was thought advisable considering the small size of the airgun pulses transmitted through the San Andreas Fault zone. It will be used as a long range source monitor, with trans-fault travel time variations compared to it. In the absence of automobile traffic and high wind conditions, the fourth borehole has a shot signal-to-noise ratio of 1/1 or better.

With the exception of the HCL telephone link, all the other lines have been tested for time stability and have been found stable to better than .5 milliseconds for periods of several hours.

The project to construct a set of FM telephone modulation and demodulation units for FM transmission of seismic signals is nearing completion. Sixteen pairs have been assembled and are currently undergoing tests or are waiting for back-orders of specific components in short supply locally.

We have acquired a good feel for the nature of the airgun arrivals at distant borehole sites and are now prepared to bring on line all boreholes in rapid succession. The processes of stacking and timing were arrived at within the last weeks as the simplest response to the considerable noise problems. Considerable experimentation with various stacking criteria and timing schemes (such as cross-correlation with source pulses, interstack multi-correlations, and digital filtering) did not appear to yield improved accuracy commensurate with increased complexity. We have not turned away from possible improvements in time resolution, but have now arrived at a satisfactory compromise which will permit data to be routinely acquired and processed.

Of no little surprise and pleasure is the observation of many arrivals following the first pulse arrival. While the paths for such late arriving energy is not now known, we are happy with the prospects that such energy samples the earth in a manner substantially different from that of the first arriving energy, and therefore may be suspected to have travel variations that differ from those of the first arrivals. If any of the later arrivals are S-waves (which can couple to a downhole hydrophone), we will have a means for compairing two velocity variations which depend on the crustal elastic constants in different ways. This may permit separating out the shear modulus versus bulk modulus contributions to velocity variations, and permit an excellent insight to the nature of the cracked-rock regime.

In addition to further exploration of the current borehole set, further boreholes within the current range are avilable for instrumentation. The computer currently has capacity for 16 boreholes, or other receiver sites.

Finally, an extensive seismic survey program to find the character of the travel paths we are monitoring will be conducted in parallel with the travel time monitoring effort. By using the precision time bases to regulate the airgun firing schedule, a refraction/reflection survey can be carried out while the computer proecesses the borehole data on a regular basis. Additional refraction/reflection data can be had by careful borehole logging, using both airgun pulses and explosion sources local to the borehole.

CREEP AND STRAIN STUDIES IN SOUTHERN CALIFORNIA

Contract No. 14-08-0001-16718

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Seismological Laboratory, California Institute of Technology
Pasadena, California 91125 (213-795-6811)

Neil R. Goulty
National Coal Board, Hobart House, Gosenvor Place
London SW1X 7AE, England (01-235-2020)

This semi-annual summary report covers the six-month period from 1 April 1978 to 30 September 1978. It is the second semi-annual report for a continuing contract. The contract's purpose has been to install, maintain, and monitor a series of strainmeters, tiltmeters, and alignment arrays across or in proximity to active faults in the southern California region. Primary emphasis has been in the Cholame and Imperial Valley areas.

During the reporting period, we have modified and replaced many of our instruments in the San Andreas fault zone in the Cholame Valley, where we have recently had difficulties with (1) flooding during the past record-setting winter rainfall season, and (2) changing agricultural land-use by the owner of the property on whose land the original installations had been made. This was a relatively major field effort, involving three new strainmeter sites (two 2-component). Four creepmeters and three tiltmeters have been repaired and restored as necessary.

The most significant signal on these Cholame Valley instruments during the reporting period was a creep episode at the Jack Ranch. About 2.5 mm of right-lateral creep occurred over a 3-hour period on 6 July, followed by an abrupt 4.4-mm slip the next day. These events were associated with only marginally diagnostic signals on the nearby strainmeters, in contrast to some earlier events. The creepmeter at Carr Ranch (3 km northwest along the fault) showed less than 1 mm of right-lateral creep during the 2-day period. The creepmeter at Work Ranch (3 km still farther northwest along the fault) showed only continuous creep over the entire reporting period -- at least to 8 August, when last observed -- as has been typical of its earlier behavior. The Twisselman Ranch creepmeter, located some 30 km southeast of Jack Ranch, is particularly important because it lies within the segment of the San Andreas fault that appears to have remained "locked" for at least 70 years, in contrast to the episodic creep behavior only a few kilometers to the northwest. This instrument was inoperative during the early part of the reporting period, but there has been no subsequent movement to our knowledge.

This was a period of rather unusual inactivity in the Imperial Valley, as reflected by the records of 4 tiltmeters, 6 creepmeters, and numerous alignment arrays maintained by Caltech in the area. The creepmeters and tiltmeters were routinely monitored and maintained twice during the reporting period (most recently on 8-22 to 8-25), and no significant anomalies were noted. Also during the period, alignment arrays were resurveyed at BAILEYS WELL, ALL-AMERICAN CANAL, HIGHWAY 80, KEYSTONE ROAD, and ANZA, with no significant changes observed.

Publications

Goulty, N. R., Burford, R. O., Allen, C. R., Gilman, R., Johnson, C. E., and Keller, R. P., 1978, Large creep events on the Imperial fault, California: Seismol. Soc. America Bull., v. 68, p. 517-521.

Goulty, N. R., and Gilman, R., in press, Repeated creep events on the San Andreas fault near Parkfield, California, as recorded by a strainmeter array: Jour. Geophys. Research.

Keller, R. P., Allen, C. R., Gilman, R., Goulty, N. R., and Hileman, J. A., 1978, Monitoring slip along major faults in southern California: Seismol. Soc. America Bull., v. 68, p. 1187-1190.

Operation of Piñon Flat Geophysical Observatory

USDIGS 14-08-0001-G-515

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This grant has helped support the field operations of Piñon Flat Observatory (PFO) for the past six months. This observatory continues to provide an uninterrupted data base on crustal deformations in an area of high seismic risk between the San Andreas and San Jacinto fault zones. The observatory, operational since 1971, consists of an array of state-of-the-art geophysical instrumentation: one purpose being to compare the best geophysical instrumentation available to establish instrumental noise levels and standards. Currently operational status of the observatory is illustrated in Figure 1.

Current Operational Improvements

1. Standby generator and automatic transfer switch with power load shedding during lightning storms.
2. Pipe support for strainmeters being rebuilt to improve the reliability--previous wooden supports have rotted.
3. Interactive editing program developed for lab computer system to speed data reduction. This program includes automatic predictive filtering to patch tidal type data across data gaps.
4. Acquisition of land, under a private bequest, is underway. Agreement has been reached with the U.S. forest Service and the University as to terms; funds are available and escrow has been opened.

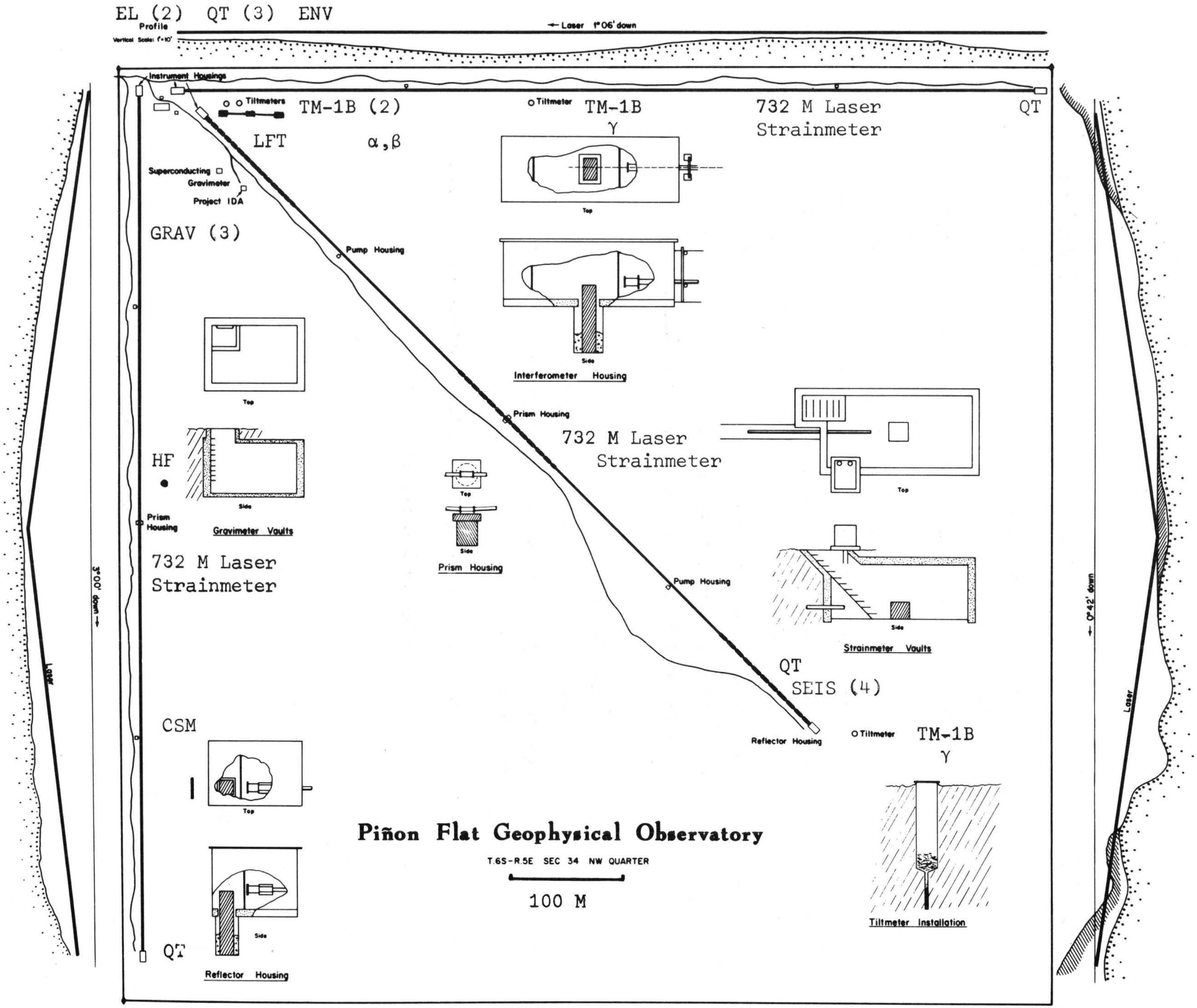
Studies Currently Underway

1. Wavenumber-frequency studies of crustal deformation to be reported at the USGS Conference on Measurement of Ground Strain Phenomena Related to Earthquake Prediction at Carmel, September 7-9.
2. Tilt noise versus strain noise (see Figure 2) from an array of Kinemetrics TM-1B tiltmeters and the laser strainmeters.
3. Comparison of strainmeter results with geodetic results of USGS in Anza array.

No. of Units	Units	Abbreviation
3	732 M laser strainmeters	LSM
1	50 M fluid tiltmeter	LFT
3	Long period seismometers	SEIS
1	Short period seismometer	SEIS
6	Quartz tiltmeters on granite columns	QT
4	Kinemetrics TM-1B biaxial tiltmeters	TM-1B
2	Superconducting gravimeters	GRAV
1	Project IDA gravimeter	GRAV
2	Electrolevels tiltmeters	EL
9	Environmental monitoring instruments	ENV
1	15 M Colo. Sch. of Mines Quartz Strainmeter	CSM
1	Heat flow well	HF
1	Recording trailer	RT
5	Multichannel digital recording systems	RT
26	Analog monitor recorders (54 channels)	RT
1	CIT/USGS stron motion accelerograph	SM

Inclusion in: USGS Anza Geodetic Array & NASA San Andreas Fault Experiment

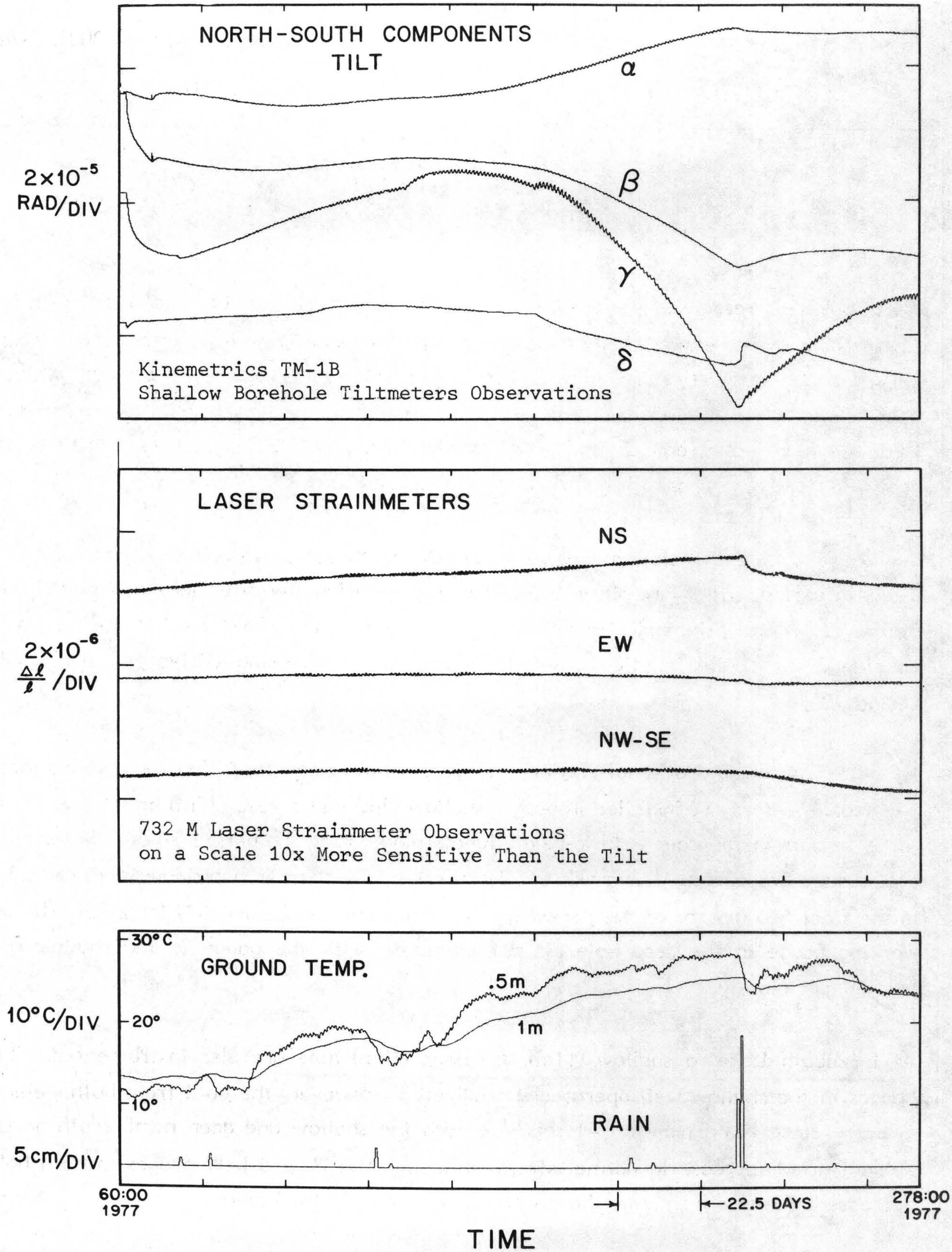
Figure 1 & Legend



EL (2) QT (3) ENV
Profile
Laser 1°06' down
Instrument Housings
Tiltmeters
TM-1B (2)
α,β
LFT
Tiltmeter
TM-1B
γ
732 M Laser Strainmeter
QT
Top
Superconducting Gravimeter
Project IDA
GRAV (3)
Pump Housing
Side
Interferometer Housing
Top
Prism Housing
732 M Laser Strainmeter
HF
Side
Prism Housing
Gravimeter Vaults
Top
Side
Prism Housing
732 M Laser Strainmeter
3°00' down
Pump Housing
Side
Strainmeter Vaults
0°42' down
QT
SEIS (4)
CSM
Reflector Housing
Tiltmeter
TM-1B
γ
Laser
Top
Piñon Flat Geophysical Observatory
T.6S-R.5E SEC 34 NW QUARTER
100 M
Side
QT
Reflector Housing
Tiltmeter Installation

F.B.3.

COMPARISON OF SHORT BASELINE TILT &
LONG BASE LINE STRAIN OBSERVATIONS



April 15, 1978

Technical Report Summary USGS Contract #14-08-0001-16746

CONTINUED MONITORING OF STRESS CHANGES NEAR ACTIVE FAULTS

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The Palmdale stressmeter net has been operating throughout the first half of FY 1978 and is returning extremely interesting data. All 20 stressmeters were installed by August 1977, but this is the first 6-month period during which all gauges were considered to be fully relaxed from the initial high stress level applied during installation. Measurements were made biweekly and a time period from October 16, 1977 to April 24, 1978 was analyzed. The results are illustrated on the attached Figure.

Three sites indicate a relative compression in the northeast-southwest direction during the 6-month period. They are shown as arrows representing the directions and magnitudes of the horizontal principal stress-change components. The other two sites show either no significant change (Lytle Creek) or a general de-stressing (Valyermo) during the period.

At Buck Canyon, our original station, the gauges have been operating for approximately one year. Sensors are installed in both a shallow (3m) and a deep (19m) hole. Two of the three sensors in the deep hole were malfunctioning during the period, so only the shallow hole results are shown. The maximum compression direction is approximately N54°E but in the final two months of the period the trend became more northerly (N32°E). The one working gauge in the deep hole did not correlate with the gauge in the shallow hole particularly closely.

At Elizabeth Lake, a shallow (11m) and deep (19m) hole are also instrumented. Two gauges in the shallow well operated sporadically. However, the data from both wells do give the same basic trends. At this site both the shallow and deep north-south gauges showed a net increase in normal stress while the N45°W and E-W gauges in both holes decreased. Results from only the deep well are shown in the Figure.

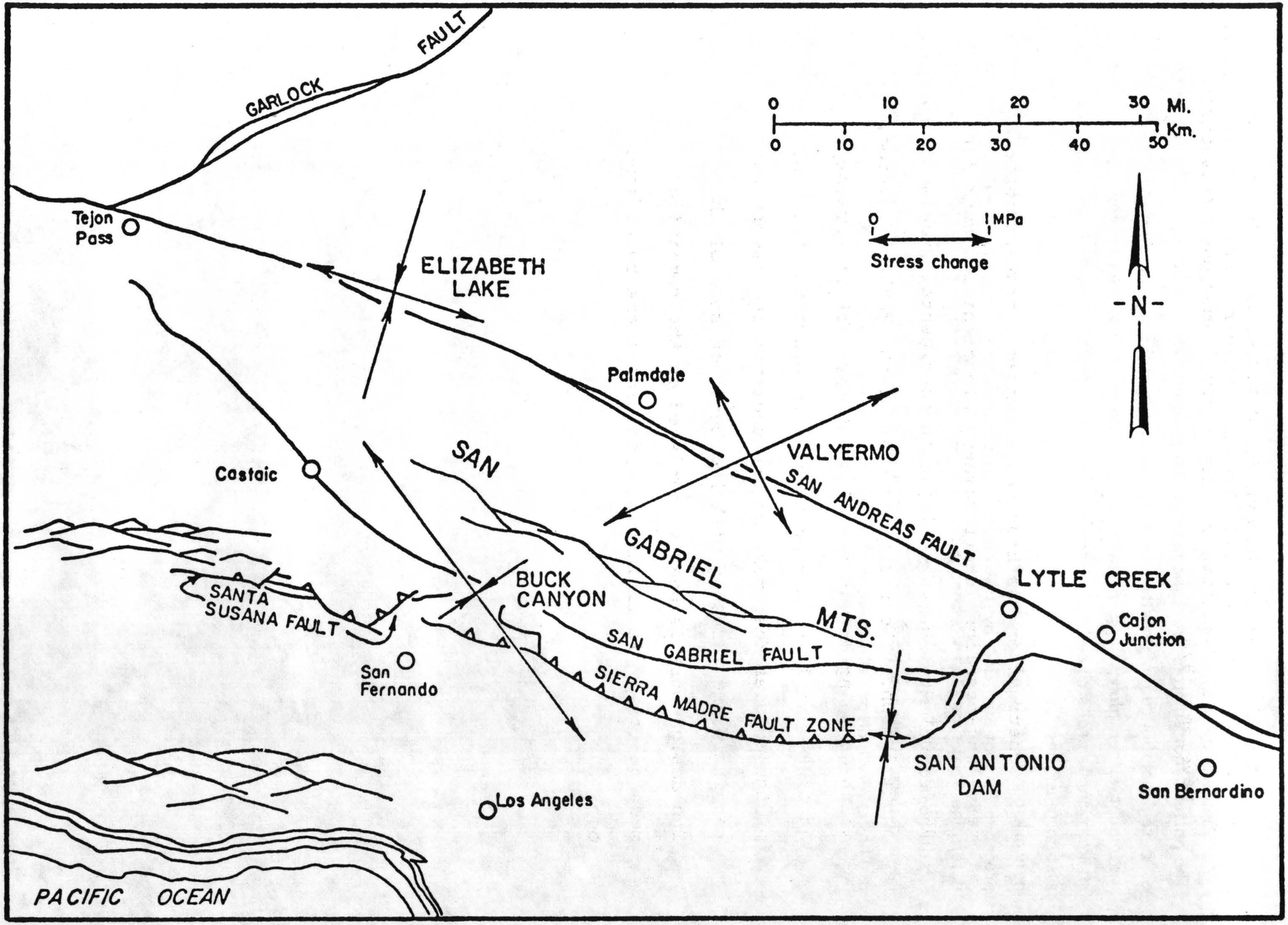
The Valyermo site is the only one that did not show an increase in compressive stress in one direction. Stresses appear to have been relieved during the 6-month period, with the greatest relief in the northeast-southwest direction. The site lies within the epicentral region of a large number of small earthquakes which occurred throughout much of 1977, but especially in the months before the stress monitoring instruments were installed. Thus, the de-stressing of the area being recorded by the stressmeters might be interpreted as a delayed near-surface response to the stress relief provided by much deeper small earthquakes.

Only two instruments were successfully installed at the Lytle Creek site. They showed only very slight increases in stress in both the north-south and east-west directions, below the limits of error for the instruments. Lytle Creek is clearly the least active of the existing sites.

San Antonio Dam units recorded a very clear signal that compressive stresses were rising in the northeast-southwest direction. The north-south gauge rose .14 MPa (1.4 bars) during the period.

Some uncertainties about the stress monitoring data are not easily dispelled. Most important is probably the degree of coupling between near-surface stress changes and changes at depths of several kilometers. Studies of coupling between shallow and deep absolute stress measurements indicate that the principal stress directions correlate well, but the magnitudes of the individual components or of the differences between components may not compare so closely. The large changes occurring at the surface indicate good coupling, but measurements at greater depths are required to confirm this conclusively. A second major concern is extrapolating data recorded at a point to a regional pattern. If the fault zone behaves as a dislocation in an elastic half space, then stresses will not change uniformly even if the far-field strains are uniform. Furthermore, the earth is heterogeneous and the regional stress field is likely to be complex. Nevertheless, the point measurements are ideal for measuring local fluctuations, possibly a much more valuable measurement for earthquake prediction than the integrative-type long-baseline strain measurements. Finally, the possibility of instrument drift cannot be completely dismissed. The data could be biased by some type of quasi-linear drift that is not consistent from gauge to gauge. However, long-term laboratory tests of the instruments indicate that they are very stable and the relative consistency of my data from one site to another at least reduces the likelihood that random drift is occurring.

The pattern that emerges from the stressmeter measurements to date can be interpreted as a regional buildup of northeast-southwest horizontal stresses that might lead to movement either along the San Andreas fault and related subsidiary faults (northwest strike, right lateral strike-slip), or along the Sierra Madre/Cucamonga/Santa Susana fault system (east-west strike, north dipping thrusts). The variations from site to site in the network can be fitted to a dislocation model for the San Andreas fault zone, but that procedure is not justified by the existing volume of data. Nor is it yet possible to determine what type of stress change signal is precursory to large earthquakes since there is still no acceptable model for the behavior of the stress field just prior to an earthquake. Nevertheless, stress monitoring is the most direct measure of ground change available yet and has a very high probability of containing useful precursory anomalies.


GARLOCK
FAULT
0 10 20 30 Mi.
0 10 20 30 40 50 Km.
Tejon Pass
ELIZABETH LAKE
0 1 MPa
Stress change
N
Palmdale
VALYERMO
SAN
Castaic
GABRIEL
SAN ANDREAS FAULT
BUCK CANYON
LYTLE CREEK
SANTA SUSANA FAULT
MTS.
Cajon Junction
SAN GABRIEL FAULT
San Fernando
SIERRA MADRE FAULT ZONE
SAN ANTONIO DAM
San Bernardino
Los Angeles
PACIFIC OCEAN

F.B.3.

Semi-Annual Technical Report for U.S.G.S. Contract No. 16759
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Massachusetts Institute of Technology, Cambridge, Massachusetts
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SUMMARY

Construction has begun on a compact, transportable very-long-baseline interferometry electronics system for subsequent use in monitoring transcontinental strain accumulation. The design is that of the Mark III system, which is being developed mainly at Haystack Observatory. As of 9 June 1978, the parts have been ordered for most of the modules that make up the receiver and recording terminal, and assembly work has begun on some of them. The design work is nearly completed on the remaining modules; as it is finished, parts orders are being sent out.

University of Minnesota

IMPROVED STRESS DETERMINATION PROCEDURES BY HYDRAULIC FRACTURING

Charles Fairhurst and M.P. Hardy

SUMMARY OF SEMI ANNUAL PROGRESS REPORT

Hydraulic fracturing as a technique for measuring in situ field stresses is based on the assumptions that:

1. a fracture will initiate when the tangential stress at the borehole exceeds the tensile strength of the rock,
2. the instantaneous shut-in pressure represents the stress across the fracture surfaces and
3. the fracture is perpendicular to the minor principal stress.

Because of uncertainties relating to the tensile strength of the rock and to the nature of the ground adjacent to the borehole, improved hydraulic fracturing techniques have been proposed. Three of these techniques are discussed in the report summarized,known as the "kickback", "σ_1 crack" and "field crack reopening" techniques. Each of these methods is shown to have strengths and weaknesses when compared with the simple "pressure-time trace to fracture" standard.

Studies are in progress to investigate the conditions required for crack reopening. To this end laboratory and analytical studies were commenced to investigate the pressure distribution down a pre-existing fracture in a compressive stress field. The laboratory study involves the formation of a crack by hydraulic fracturing after which this fracture surface is used in an essentially one dimensional parallel flow situation. The fluid is contained laterally by a sealer inserted in grooves cut into the halves of the original block, before it is rejoined and subjected to normal stress. It is expected that pressure drops of up to 500 psi along a 10 inch fracture path will be observed, and normal stresses up to 5000 psi will be employed.

Analytical and numerical studies of the above experiment have been undertaken. A displacement discontinuity model for the stresses has been coupled to a one dimensional analytical model for the fluid flow. The analysis is currently being extended to cover the case of transient flow, incorporating fluid compressibility and flow resulting from crack opening. Pressure-time records will be produced and compared with laboratory records. The model is also being used to examine the so-called "kickback" phenomena and to try to reproduce the secondary breakdown pressures and shut-in pressures when the crack path is curved.

Laboratory studies are in progress to investigate the effect of the stress field orientation on the induced hydraulic fracture. A triaxial cell capable of applying over 2500 psi to 15 inch rock cubes is under preparation. Investigation of sites for sample collection for this large cell is underway.

Results are presented from field investigations of hydraulic fracturing. The tests were carried out at a site at which overcoring stress measurements had also been made, giving a unique opportunity for the evaluation of the two stress measurement techniques applied to a single site. Although the interpretation of the test results is not yet complete the general conclusion reached is that the hydraulic fracture tests give results consistently lower than the overcoring tests. Kickback experiments, when performed, were inconclusive, but it appears that the phenomena is due to some other mechanism than crack reopening and consequent flow in the crack and is probably related to transients in the test equipment. Further field studies are required to investigate the *in situ* fracture adjacent to the borehole.

Continuation of the present work will include:

1. crack reopening studies on a single hydraulic fracture,

2. methods of initiation of a crack perpendicular to the major principal stress, and
3. study of hydraulic fracturing when the borehole axis is not a principal stress direction.

These studies will be aided by the introduction of the new triaxial cell, and will proceed in parallel with the analytical work previously outlined.

Oct. 1, 1977-Mar. 31, 1978

TILT MEASUREMENTS IN THE NEW HEBRIDES ISLAND ARC: SEARCH FOR ASEISMIC DEFORMATION RELATED TO EARTHQUAKE GENERATION IN A MAJOR ZONE OF LITHOSPHERE SUBDUCTION

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TECHNICAL REPORT SUMMARY

During the period covered by this report no large earthquake (M_s >5.5) occurred close to the tiltmeter network. The moderate activity characteristic of the past twenty months of tiltmeter operation has continued, but has produced no clearly detectable precursory signal. The largest and closest events so far recorded include five events with magnitudes (m_b) between 5.0 and 5.4, recorded at straight-line distances between 37 and 60 km from the nearest tiltmeter station. Four of these were shown in Report #2, and the fifth is reported here. Further examination has also been made of the large September 4, 1977 event (M_s = 6.5) located 155 km from the nearest tiltmeter station. No clear precursory signals are seen for these events at a resolution of about 10^{-7} for periods up to several hours, as determined on the original Rustrak records. Digitization and replotting of the data at compressed time scales indicates increased noise at longer periods, and the resolution worsens to about several microradians. Rainfall is clearly the dominant source of transient noise in the range of periods between several hours and several weeks. The continuous recording of rainfall accumulation that has been successfully initiated at several stations will significantly increase the signal detection capability.

This report covers a six-month period after the field season of August-September, 1977. The new tiltmeter station (Tukutuk) on Vate island worked reasonably well, as did five of the remaining seven stations. Two of the initially rainfall sensitive stations have shown increasing problems with rainfall in spite of attempts to improve the stability of the site. It appears that the local ground conditions are simply not adequate for tiltmeter stability, and these stations will have to be moved during the forthcoming field season.

Experiments were performed at the Devil's Point tiltmeter station to determine the cause of the long term drift characteristic of one of the components of that station. As described in Report #1, the leveling results did not verify the drift indicated by the tiltmeter. Experiments included a substitution bridge to replace the tiltmeter bubble-level and a prototype electronics of the improved design loaned to us by Kinemetrics. The experiments show that the drift is not tied to the electronics, nor is it improved by the newer electronics, but appears to be either in the bubble level itself or in the immediate siting of the instrument. If the latter case is right, then it must be considered a somewhat remarkable coincidence that the direction of drift is so closely aligned to one of the tiltmeter components.

The new tiltmeter recording systems, including an additional slow-speed Rustrak which records both tilt and rainfall, has proven to be very effective. Improved versions of the system have been constructed and tested and will soon be installed at all stations. Development of the microprocessor controlled digital recorder has continued and production of these units will begin after the further testing of the second prototype. In addition to the advantages of digital recording, the microprocessor unit will be a key component in linking the tiltmeter data to a central base station via the new VHF telemetry system that will be installed for the seismograph network.

A study of the tidal signals recorded by the tiltmeters has been completed and the manuscript is being prepared for publication. The study shows that the large tidal signals are caused by loading of the ocean tides in an area close to the tiltmeter. This effect can be explained by a two layer model with a low-rigidity near-surface layer. The anomalously large amplitudes at one station appear to be an effect of the large amount of porosity of the coral rock at the site, an effect which either reduces the rigidity of the rock or allows the load to be applied closer to the tiltmeter than the nearby coastline.

A Lamont-type sea level recorder was installed at Southwest Bay in September 1977. Three months of record are available for this instrument. It is operating in a sand beach and utilizes the sand as a tidal filter. Unfortunately the filter is too effective, and the tides are just barely perceptible at a full-scale sensitivity of 10 cm in water level. This implies an excessively long time constant, and the instrument will be moved to a location closer to the water in an attempt to decrease the time constant. Comparison of the sea level record with the nearby tiltmeter shows a correlatable small amplitude oscillatory signal with a period of one to three weeks. The relative polarities of these signals are in agreement with an ocean loading effect.

Levelings of the two arrays of benchmarks were done during the period of the report. The Devil's Point array remains stable at the microradian level. The Ratard results are still being reduced. Three additional benchmarks were installed at Devil's Point to strengthen that array, and were included in the most recent levelings.

Work of potentially great significance to the tiltmeter program is being done in cooperation with A. Bloom and F. Taylor in their studies of uplifted coral terraces in the New Hebrides. Preliminary results of this work was presented at the Miami meeting of the AGU (April, 1978). The pattern of uplift associated with the sequence of large earthquakes in 1965 was examined and found to be consistent the longer term pattern of Holocene and Late Pleistocene uplift. Evidence is found both in the earthquake related movements and the longer term motions for possible block-like units defined by discontinuities in tilt alone as well as by presumed discontinuities in vertical motions.

Semi-Annual Technical Report #3

April 1, 1978 - September 30, 1978

TILT MEASUREMENTS IN THE NEW HEBRIDES ISLAND ARC: SEARCH FOR ASEISMIC DEFORMATION RELATED TO EARTHQUAKE GENERATION IN A MAJOR ZONE OF LITHOSPHERE SUBDUCTION

Report prepared by Bryan L. Isacks, Principal Investigator, and Richard Cardwell

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TECHNICAL REPORT SUMMARY

A network of seismograph stations was installed in the central New Hebrides during the field season of July-October, 1978 by the seismological research groups of Cornell University and the French Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM). The network consists of ten vertical-component, short-period seismometers (see the attached figure). To obtain good shear wave data horizontal-component seismometers were also established at EPI and SWB stations. This twelve-component network supplements the existing ORSTOM multi-component stations at PVC, LUG, and LNR. All data produced by the twelve components are transmitted by VHF radio telemetry to a central recording station at PVC on Efate island, using the links shown in the figure. At PVC the signals are input into a triggered, event recording system that was developed by the University of Texas. This system uses electronic triggering and a digital memory to record events on a Siemens multi-channel oscillograph. The result is a clear, high-resolution record. The data from all twelve components are written on one sheet of paper with a common time base. This network provides adequate spatial coverage of the central region of the New Hebrides arc, and will greatly improve the resolution of the time-space pattern of seismicity. To calibrate the seismograph network, a combined land and Ocean Bottom Seismograph (OBS) experiment was run in cooperation with the University of Texas. The eight OBS units were located as shown in the figure, and together with the land stations provide excellent hypocentral control for the shallow events in the arc-trench gap. During the six week experiment the triggered, analog recording system (Siemens) was operating in addition to a triggered, digital recording system (portable Sprengnether instruments) and a continuous, analog recording system (MEQ 800). Over 600 events were recorded including several events that were large enough to be located teleseismically by the USGS. Data from this experiment is being analyzed.

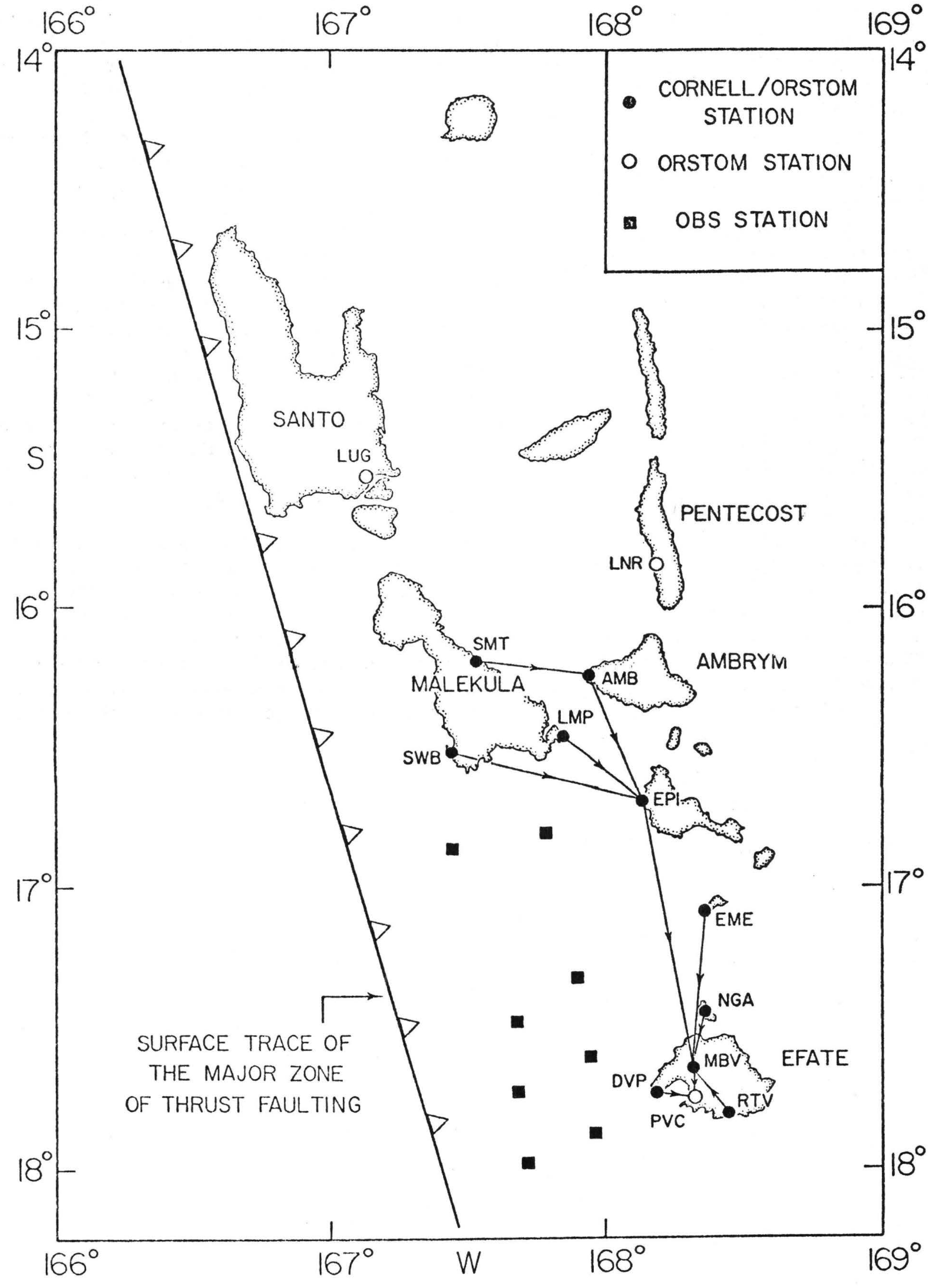
During the period covered by this report no large earthquakes (M_S > 5.5) occurred close to the tiltmeter network in the central part of the New Hebrides arc. The moderate seismic activity of the past 26 months has continued. Nine shallow earthquakes with magnitudes (m_b) between 5.0 and 5.5 were recorded in the vicinity of the tiltmeters, but no clearly detectable precursory signals have been observed for these events at the resolution of about 0.1 microradians.

The eight station tiltmeter network continued to operate successfully and new recording systems were installed at many of the stations. The new recording system includes a second Rustrak recorder running at slow speed which compresses the time scale of the tilt data. This system also records data produced by the raingauge instruments. Since rainfall signals are an important source of noise at periods of hours to weeks, the new recorder will be extremely useful for identifying this source of noise.

The arrays of benchmarks at Devil's Point on Efate and Ratard on Santo were releveled during the period of this report, but the results have not yet been reduced. So far in the New Hebrides the leveling technique has provided the best data on tilt that are stable over long periods of time.

Two liquid-level tiltmeters were installed during the field season to provide tilt measurements over a baseline of intermediate length between that provided by the long baseline geodetic releveling technique and the short baseline, bubble-level, bore-hole tiltmeters. This type of instrument will provide continuous measurements that are stable over the period of days to months in which the bore-hole tiltmeter records show increasing noise. These liquid-level tiltmeters are modifications of those operated by the research group of the Lamont-Doherty Geological Observatory. Each liquid-level tiltmeter consists of a buried-tube half-filled with water with specially built reservoirs at each end of the tube. The liquid levels in the two reservoirs for each tube are monitored with a micrometer. Four independent liquid level measurements are taken to obtain the direction of tilt. This simple sensing technique can obtain a sensitivity of about 0.1 microradians of tilt.

Two tubes of 100 meters length each have been installed on a flat coral terrace at Devil's Point, Efate. The tubes are oriented parallel and perpendicular to the trend of the New Hebrides trench. An automated system that electrically senses the water level and records the information on a Rustrak recorder has been developed and will be installed before the end of the year. Since the water-tube tiltmeters are located near the Devil's Point borehole tiltmeter and the geodetic leveling network we now have a means of evaluating the consistency of tilt measurements determined by three separate techniques.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SURFACE TRACE OF
THE MAJOR ZONE
OF THRUST FAULTING

Tilt, Strain and Magnetic Field Measurements

8-9960-01189

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Investigations

1. Integration of data from arrays of tilt, strain, magnetic field, creep, seismic and other measurements.

2. Development of techniques to identify the near surface noise spectrum and wave number spectrum for tilt and strain measurements with a number of 50 to 200 m deep boreholes containing tilt and strain instruments. A prototype of these instruments has been built. These data will be used in conjunction with data from existing clusters of instruments.

3. Maintenance and expansion of the digital data system used to collect, display and analyze these data. Installation of an interrogatible, special purpose μ processor based digital telemetry system at several sites for field testings. The prototype system is presently working over commercial-grade telephone lines.

4. Continue an attempt at regional monitoring of crustal stress-variations using a repeated magnetic survey techniques.

5. Develop tectonomagnetic models of particular sections of active faults where magnetic field changes have been observed.

6. Develop tectonic models of further types of crustal behavior along active faults.

7. Continue large scale continuous crustal tilt measurements using a system differential level measurement on existing dams and aquaducts.

8. Continue searching and testing specifically defined earthquake precursor functions. With the present analysis system it is expected that at least 50% of earthquakes, $M_L > 3.5$, that occur near instruments will be identified before that occur. However, unless more moderate magnitude earthquakes occur within instrument arrays these studies will be restricted to the minor earthquakes where the signals are small and ambiguous.

Results

1. Resurveys of the local geomagnetic field in southern California, using differential magnetometers, indicate the development of an anomalous field of more than 10 gammas that appears to correspond to the partial collapse of the southern California uplift, reported by Castle et al., (1977). The 10 gamma

field increase occurred within a 30 km fault segment near the junction of the San Andreas and San Jacinto faults. It occurred episodically in time with 80% accumulating between late 1973 and the end of 1974 and the remaining 20% between 1974 and 1976. Changes of smaller maximum amplitude and opposite sense occurred to the southeast along the San Jacinto fault. Swarm seismicity occurred at the northwest end of the zone of maximum anomaly since late 1976 but ceased in late 1977 (McNally et al., 1978). The anomaly amplitude has slowly decreased with time since its peak in 1976. Tectonomagnetic models imply localized stress changes at depth of at least 10 bars in the vicinity of the magnetomeer sites near the various faults although details concerning the geometry and dimensions of the region responsible for the magnetic field change are poorly resolved.

2. Transient tilts associated with numerous fault creep observations have been recorded at several selected locations along the San Andreas fault at these locations episodic fault displacements of 1 to 5 mm typically occur over a period of an hour or so. Maximum tilt amplitudes are less than 0.5 μrad at observation points less than 0.5 km from regions. Clear tilt transients have not been observed at distances from 1 to 2 km from the fault. An array of four tiltmeters is installed at one location around five creepmeters. Simple dislocation models of creep events observed on these instruments indicate shallow and sometimes complex regions of fault failure apparently resulting from and triggered by, slower and more uniform slip at depth. Components of dip-slip displacement, evident also in the surface topography at this location, are sometimes necessary to explain the near-surface tilt observations. Longer term tilts perhaps related to slower fault slip at depth are sometimes evident at distances of 1 km from the fault, but the form of the signals is not what would be expected from simple models, nor is it consistent for different events.

3. A data management and analysis system has been designed to provide control and rapid analysis capability in dynamic research environments such as in the fields of earthquake mechanics and prediction. This general computer based data retrieval and analysis system -- GEOLAB -- allows easy access to, display, integration, and analysis of all data through a simple interactive command language and both interactive and offline graphics devices. This software system provides a stable laboratory environment where various mathematical, statistical, and graphical tools are immediately available to operate on designated data so that ideas may be tested and sheared expeditiously. New tools may be easily added or combined by any user thus increasing the vocabulary of 'operators' which has broadened to include many specialized applications including detection of telemetry noise, spectral analysis, and correlation of simultaneous data from many instruments. The same GEOLAB system is used in production mode in the near real time analysis of earthquake precursors using operators that look for signals having specifically defined character.

4. Data from several tiltmeters and several creepmeters along the San Andreas fault in central California 30 km south of Hollister were selected to investigate tilt perturbations of minutes to hours duration. The distribution in space and time of short-period tilt events suggests that most are due to causes other than slip on the San Andreas fault, such as local strain release. However some creep-related tilt events have been observed. Dislocation models

capable of reproducing the creep-related tilt events have been constructed to examine the relationship of the model parameters, including source-station geometry and displacement time history, to the details of the tilt waveforms. These models suggest that at least some creep events of short duration are associated with finite size slip zones of shallow depth.

5. Many lakes exist in or near active fault zones. Crude indications of crustal deformation at intermediate scales (2-10 km) can be obtained by using the essentially equipotential surface of the lakes and monitoring the lake level at different points. A prototype differential level system consisting of two ultra-stable quartz pressure transducers was installed in San Andreas Lake, California in March, 1978. The sensors are 4.3 km apart and have measurement precisions and stabilities of better than 0.1 mm of water and 3 mm of water/yr respectively. Seiches of amplitudes of 2.5 mm (.5 - 1.25 μrad) are easily observed. Their period of 15 minutes agrees closely with the period calculated from a simple model of the lake. The seiches, along with tides, waves, thermal and atmospheric pressure gradients prevent accurate short term tilt measurements to better than + 0.8 μrad. Total drift during the first three months of operation has been 1.5 μrad. down to the southeast.

6. The Data Collection Node (DCN) has been designed and constructed. This is a portable field telemetry device which samples, processes, stores and transmits field data. The transmission follows receipt of a telephone call and is over commercial, voice grade telephone lines. The flexibility of the DCN allows expansion of storage space, analog inputs and digital inputs. The specific operating characteristics of the device are determined by a modifiable and expandable program module.

A field test conducted for several months on the San Andreas Fault has verified proper functioning of the DCN in digitizing, averaging, storing and transmitting tiltmeter data. The DCN promises to be a general purpose, low cost, low power and flexible solution to low frequency field data acquisition.

7. Three years of data from several strainmeters installed within two kilometers of the San Andreas fault indicate almost pure right lateral shear at rates of 4 to 6 μstrain/year with the maximum principal compressive axis in directions from N16^{0}E to N28^{0}E. Near these installations the fault is both seismically active and actively creeping. In contrast, data from a similar strainmeter installed at a distance of 10 kilometers from the locked section of the fault indicates compressive strain at a rate of less than 0.45 μstrain/yr in a direction N17^{0}E. This is in approximate agreement with geodetically determined strain rates in this area. Similarly, tilt rates measured within a few km of the fault differ by a factor of ten or more from those measured at a 10 km distance from the fault. These data would support a fault model whose main characteristic is rigid block type behavior and for which concentrated shear strains would occur in a weakened zone near the fault at least several kilometers wide.

Present geodetic data (Prescott and Savage, 1978; Slater and Huggett, 1976) and seismic data (Stierman, 1977) provide independent support for this model in the creeping section of the fault. Although possibly ambiguous, strain changes due to changing or accelerating slip at depth should be most easily detected within this shear zone.

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DIRECT DETERMINATION OF STRAIN ACCUMULATION NEAR ACTIVE FAULTS FROM MEASURED GEODETIC DATA

Contract Number: 14-08-0001-16828

Principal Investigators: Robert D. Lynch and Joseph A. Lahoud

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Summary of Semi-Annual Technical Report for the Period February to August, 1978

Much has been learned about strain accumulation along the San Andreas fault through analyses of geodetic data. Virtually all triangulation and trilateration data have been analyzed in the past using a strain accumulation model which assumes that the components of strain are constant. There is ample evidence, however, beginning with the 1906 San Francisco earthquake, that the strain field is in fact not constant but rather is a function of position with respect to the fault. In this study, geodetic data are analyzed using a nonuniform strain accumulation model based on dislocation theory.

The model adopted for this study contains three parameters: (1) the relative velocity between the Pacific and North American plates, (2) the depth of the fault and (3) the cumulative offset at the fault caused by either fault creep or earthquakes. The model is used to derive equations relating geodetic observations to the model parameters. These equations are used, in turn, to develop a non-linear statistical analysis procedure to provide numerical estimates of the model parameters.

The purpose of this study is to determine if the nonuniform strain accumulation model will adequately account for observed changes in geodetic data measured in the vicinity of an active fault. For this purpose, two areas in central California have been selected for study. The first area is near Cholame where the San Andreas fault is the only active fault in the area and thus provides a relatively ideal setting for testing the model. The second area is a more structurally complex area near Hollister where both the San Andreas and Calaveras faults are active. For this more complicated case, two models will be superimposed and used.

Specific accomplishments for the first six months of this study are as follows:

1. A model based on dislocation theory was selected and generalized to include both strain accumulation and strain relief.
2. Equations relating geodetic observations to the model were derived.
3. Non-linear statistical analysis procedures for triangulation data were developed, programmed on a digital computer and tested using simulated data.
4. Triangulation data from the Cholame area and trilateration data from the Hollister area were collected.
5. From the Cholame triangulation survey data, the dependent variable (angle change) and the independent variables (x , y coordinates of the survey marker points) were computed.

Preliminary results have been obtained from an analysis of data from Cholame triangulation surveys conducted in 1932 and 1962. For the 30-year interval, the analysis gives a relative plate displacement of 107 cm and a fault depth of 19.2 km. An initial examination of data from points on opposite sides of the fault indicates approximately 4 cm of fault offset during the 30-year period. The average relative plate velocity is 3.57 cm/year. Shear strain is accumulating at the fault at a rate of $-0.28\,\mu$ strain/year. The relatively small fault offset of 4 cm, presumably due to fault creep, has provided only minor strain relief over the 30-year period examined. These results are tentative, since the question of model validity remains to be resolved.

Tilt Operations

8-9960-01801

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Goals

The Tilt Operations project will operate extensive networks of telemetered tiltmeter sites in central and southern California, and a few sites in Alaska, along seismically active and creeping faults in order to study the mechanics of seismic and aseismic fault slip and other processes that may relate to earthquake prediction. Goals for the second half of FY 78 include continued evaluation and upgrading of system performance to ensure future data quality. Instruments will be deployed at several sites where boreholes of 30-60 m depth have been prepared in order to investigate the characteristics of surface tilt signals and noise with respect to wavelength, period, and depth dependence.

Important non-scientific goals of the project include providing logistic and technical support to other projects, particularly the magnetometer, strainmeter and creepmeter programs. Technical support will also be provided to contract maintenance personnel throughout the life of the maintenance contract.

Investigations

The tilt operations project continued the search for tilt precursors to earthquakes in California and Alaska, specifically by operating and monitoring the tiltmeter arrays in central and southern California, totalling 80 sites, and an array in Alaska consisting of three sites.

Quality control was provided on tilt data received by monitoring telemetered data and occasional comparison with level array data. Plots representing an extensive set of hand cleaned data were produced and used to characterize the tiltmeter data generally. Automation of the cleaning process was accomplished and comparison with the results of hand cleaning has been undertaken.

Six boreholes of 30-60 m depth have been drilled at three sites in central California in order to study effect of instrument baseline and depth dependence of ground tilt signal-to-noise ratio. At the Nutting site, boreholes of 30 and 45 m have been completed, though driller's mud remains to be removed from these holes. Two boreholes near San Juan Bautista have been completed to depths of 51 and 60 m while at the Gold Hill site, near Parkfield, boreholes of 52 and 60 m have been completed. These boreholes have been cased with heavy walled casing of 22 cm diameter grouted securely in place with a stablized expansive cement.

A prototype long-baseline borehole tiiltmeter was installed at the Stone Canyon tiltmeter site within 25 m of the existing installation in order to evaluate the practicality of the technique and to compare the noise level with a standard short-baseline installation. The approach involves monitoring horizontal displacements near the top and bottom of the borehole by measuring rotation angle of a reference column using a standard Kinemetrics tiltmeter as a sensor. The reference column is decoupled from vertical displacement gradients (due to thermal gradients or vertical ground strains), that might cause spurious buckling, by a vertically compliant diaphragm. Initial results cannot be safely interpreted due to a malfunctioning sensor.

A tiltmeter site near Hughes Lake, California, which has been unuseable due to ground water intrusion since the heavy rainfalls of last winter has been restored. Waterproofing of all equipment at this site is being undertaken to obviate similar problems in the future. This site affords the opportunity to evaluate the relative performance of the Kinemetrics tiltmeter and the Hughes TM-3 tiltmeter at a burial depth of 6 m. In the brief period of operation prior to flooding the instruments tracked each other closely for roughly one month and possibly showed an improved thermal response. It was felt that these results were sufficiently encouraging to warrant the restoration effort.

In an effort to determine the importance of the effects of slight bending of the instrument casing during emplacement of the Kinemetrics bubble-level tiltmeter, a very thick and rigid stainless steel case is being manufactured. It should be possible with this test to establish whether the source of the reversal of response observed during emplacement is the instrument casing or the surrounding sand pack. Any change in the character of the data will provide an indication of the nature of a spurious response resulting from the reversal phenomenon.

Results

Examination of an extensive set of hand cleaned tiltmeter data has provided a general insight into the characteristics of such data from a broad range of periods for a wide variety of site conditions. These data were carefully inspected and processed to account for a variety of spurious signal sources ranging from instrument adjustments and malfunctions to telemetry and automatic processing errors. The task required between 3 and 4 man-years of work and has now largely been supplanted by improved automatic processing.

Preliminary results from analysis of these data indicate that long term secular tilt rates range from 1/2 μradians per year to 50 or more μradians per year with typical values ranging between 5 and 20 μradians per year. Tests at the San Francisco Presidio vault and comparison of tilt measurements from the Presidio and Berkeley vaults with measurements from shallow borehole tiltmeters along active sections of the San Andreas and other faults imply that it should be possible to measure long term tilt with a stability on the order of 1 μradian per year with the shallow borehole installations. The results further suggest that secular tilt rate may be inversely related to distance from the fault. The analysis also indicates that the noise level and response to spurious signal sources of short-baseline tiltmeter measurements, in all period ranges, are critically dependent on local site conditions, with each critical feature having its own frequency dependent response.

Reports

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SUMMARY OF FINAL REPORT

October 1, 1977 - September 30, 1978

RECENT VERTICAL MOVEMENTS OF THE CRUST IN THE WESTERN UNITED STATES: REDUCTION AND ANALYSIS OF LEVELING DATA AND ITS INTERPRETATION IN LIGHT OF RELATED SEISMOLOGICAL AND GEOLOGICAL INFORMATION

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Report prepared by Robert Reilinger

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Introduction

The goal of this study is to provide a better understanding of the relationship between recent crustal movements, primarily as determined by leveling and earthquakes in order to reduce the earthquake hazard. Our method consists of determining those leveling routes for which at least two levelings separated significantly in time exist. Comparisons are then made to estimate differential movements for benchmarks along the profile. Interpretation entails analyzing these results in the perspective of what is known about the relevant geology and tectonics as well as evaluating existing theories in light of the new information provided by leveling data.

Recent Results

I. Recent Vertical Crustal Movements from Leveling Observations in Seismically Active Areas in the U.S.

Crustal movement studies are divided by tectonic setting, including: the San Andreas fault and related tectonic elements in California, the Nevada seismic zone, the Intermountain seismic zone, the Rio Grande rift, Alaska and subduction related deformation, and Hawaii. A review of the published information indicates that the most prominent vertical crustal movements detected by leveling observations (excluding subsidence due to fluid withdrawl) are those associated with major earthquakes. Vertical crustal movement information on various phases of the earthquake cycle have been reported for the 1933 Long Beach, California earthquake, the 1952 Kern County earthquake, the 1954 series of moderate earthquakes along the Nevada seismic zone, the 1959 Hebgen Lake, Montana earthquake, the 1964 Alaska earthquake, the 1971 San Fernando earthquake, and the 1975 Oroville earthquake. In addition, leveling has been used to determine the rate of strain accumulation in areas of potentially destructive earthquakes. These studies suggest that, at least in some cases, measurable vertical displacements of the ground surface are associated with all phases of the earthquake cycle (pre-, co-, post-seismic, and secular). This adds credence to the hope that monitoring vertical movements of the crust may eventually provide an effective means of forecasting potentially destructive earthquakes.

Surface deformation thought to be associated with intracrustal magmatic activity has been observed in Hawaii, the Rio Grande rift, and in the Yellowstone park region. Broad aseismic deformation has been reported in the lake Bonneville region of Western Utah, in the Sierra Nevada range in northeastern California and in the vicinity of the "big bend" in the San Andreas fault in southern California (Palmdale bulge). Additional measurements are needed to evaluate the significance of regional patterns of deformation and help determine their cause.

II. Apparent uplift North of San Francisco: Unusually large errors in the 1935 leveling Survey

Apparent vertical crustal movements determined from comparison of leveling surveys conducted along the northern locked section of the San Andreas fault in 1935 and 1942, in conjunction with the continuous tide guage record at San Francisco, suggest rapid uplift during this period along at least a 150 km segment of the fault between San Anselmo and Point Arena, California. Maximum observed uplift of about 23cm relative to sea level occurs approximately 90 km north of San Francisco. Although the apparent movements are more than five times larger than those that can be attributed to random error, unusually large circuit misclosures cast serious doubts on the reliability of the 1935 survey. Possible causes for the large misclosure are being investigated. Loop closure analysis, which are well known to geodesists, have received little attention in many vertical crustal movement studies. This technique is being used to investigate reported vertical movements in a number of other areas in the United States.

III. Vertical Movements along the West Coast of the U.S.

A profile of relative vertical crustal movements has been compiled from leveling data along the west coast of the United States. Comparison of this profile with one obtained from secular trends in sea level reveals a serious systematic disagreement between the two methods. Normal measurement error and the inhomogeneous nature of the leveling data may account for some of the misclosures indicated. Although the cause of the discrepancy is poorly understood, this comparison makes it possible to estimate the magnitude of the discrepancy, a major step toward identification of its cause. Comparison of these profiles with topography and gravity indicate some weak correlations; more positive correlations exist with seismicity and known faults or contacts between major structural units.

IV. Assesment of Geomorphic evidence of recent tilting

Many leveling routes run along river valleys parallel to large rivers. Since rivers tend to maintain their grade any tilting of the river bed should be reflected in changes in the drainage pattern or more precisely the meander ratio (ratio of river length to valley length). Where the valley slope is being over-steepened by tectonic tilting, the river can maintain a constant gradient by becoming more sinuous and increasing the meander ratio. Where gentled by tilting, rivers can maintain their grade by straightening their channels and so decreasing the meander ratio.

Preliminary results from application of this method to profiles in the midwest suggest that many of the geodetically determined tilts are real, have a short term, oscillatory nature ($T \cong 10^3$ yrs.) and probably are of crustal or upper mantle origin.

V. Interpretation of Vertical Crustal Movements in Intraplate Areas

A comparative analysis is made of elevation changes in four different intraplate areas in the U.S. - the Rio Grande rift of Central New Mexico, the Hebgen lake region of Montana (site of $M_s = 7.1$ earthquake), the Gulf Coastal Plain of Louisiana and Mississippi and the Appalachians of North Carolina. These examples are used to deduce specific criteria for evaluating the reliability of leveling estimates of crustal deformation. This comparative analysis emphasizes that in spite of the uncertainties inherent in leveling measurements, they are an important and still under-utilized source of information on intraplate tectonic processes.

VI. Recent Vertical Crustal Movement in the Rio Grande Rift

Analysis of repeated leveling surveys indicates contemporary vertical deformation in at least three distinct areas in the vicinity of the Rio Grande rift. These areas include Socorro, New Mexico; the Espanola basin northeast of the Jemez mountain and the Diablo Plateau region of Trans-Pecos, Texas. Deformation in all three areas can be related, with different degrees of uncertainty, to crustal magmatic activity. These observations suggest that the rift is currently active and that crustal magmati activity plays an important role in the neotectonics of the Rio Grande rift system.

Recent Publications

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Crustal Strain

8-9960-01187

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Investigations

Measurement and analysis of strain accumulation in central and southern California was the principal subject of investigation although some measurements and analysis were undertaken in Utah, Montana, and Washington. Some analysis of data from Canada and Guatemala was also undertaken. A detailed search of the measurements was made to detect possible earthquake precursors with negative results.

Results

1. The plate tectonics model of the Pacific moving northwest relative to North America implies that the regional strain in California should be simple shear across a vertical plane striking N.45°W. or equivalently equal parts of north-south contraction and east-west extension. We have measured the strain accumulation at seven separate sites in southern California in the interval 1972-78 and find a remarkably consistent uniaxial north-south contraction of about 0.3 ppm/yr; the expected east-west extension is absent. It is not clear whether the 1972-78 secular strain in southern California is indeed a uniaxial north-south contraction or a systematic error has contaminated the measurements. The strain field is inferred from repeated precise distance measurements, and a systematic error would manifest itself as an apparent isotropic dilatation. The addition of the proper amount (0.30 μstrain/a) of isotropic dilatation to the observed uniaxial north-south contraction would produce the expected pure shear strain. We are unable to identify such a systematic error in our measuring system, but we do observe a negative dilatational strain in almost all of our strain networks. Our tentative conclusion is that the negative dilatation is a real effect and that strain in southern California is indeed a uniaxial north-south contraction, but caution is advised in accepting this result.

2. A trilateration network extending across the San Andreas, San Jacinto, and Elsinore faults in the vicinity of the Salton Sea has been surveyed to very high precision several times in the five-year interval 1973-77. The average strain across the entire network is a uniaxial north-south contraction at the rate of about 0.3 μstrain/a. The absence of a substantial strain rate perpendicular to the Salton trough indicates no tendency either to open or close that rift. The observed uniaxial north-south contraction differs from a pure shear parallel to the major faults by a uniform dilatation of about -0.25 μstrain/a that is only partly explained. The shear strain distribution across the network reaches a maximum near the San Jacinto fault and could be explained by right-lateral slip at depth on that fault. The displacement pattern also suggests right-lateral slip at depth on the San

Jacinto fault with total right-lateral relative movement near 50 mm/a across the 120-km breadth of the network. The deformation appears to be uniform in time in the 1973-77 interval. A dislocation model of the deformation suggests about 50 ± 15 mm/a of relative right-lateral slip at depth distributed between the San Andreas, San Jacinto, and Elsinore faults and demonstrates that a significant average dilatation can be generated by pure strike slip on several subparallel faults.

3. Annual Geodolite surveys of a geodetic network spanning the San Andreas and Calaveras faults near their junction provide data to calculate the relative motions of the geodetic stations. Except very close to the junction of the two faults, the deformation can be described by rigid-body translation of the three blocks defined by the faults. The rigid motions are accommodated by strike slip on the San Andreas and Calaveras faults. The total relative motion across the 35-km breadth of the network is about 30 mm/a in a direction (N.30^{o}W.) intermediate between the strike of the San Andreas and Calaveras faults. The average slip rate on the San Andreas fault is about 13 mm/a and on the Calaveras fault about 17 mm/a according to the rigid-block model. The relative velocities of the blocks appear to change during the 1971-78 interval.

4. A recent re-examination by Rogers and Hasegawa of the available seismic data from the June 23, 1946 Vancouver Island earthquake (M_S=7.2) indicates that the earthquake was of relatively shallow (30 km or less) focal depth and the epicenter was located in central Vancouver Island rather than beneath the Strait of Georgia some 30 km or more to the east as previously thought. Savage and W. F. Slawson (University of British Columbia) have tested the Rogers-Hasegawa solution by resurveying a triangulation network in the epicentral areas which had first been surveyed in 1935. The distortion of the network was found to be much greater than could be accounted for by either secular strain accumulation as indicated by measurements of a nearby network or survey error but is consistent with oblique slip on a segment of the Beaufort Range fault, a prominent fault that crosses the triangulation network. The best model for slip on the Beaufort Range fault involves 1.00 ± 0.25 m right-lateral and 2.50 ± 0.65 m normal slip on a shallow (0 to 5 km) segment dipping 70^{o}NE. However, pure right-lateral slip of about 1 m over a depth interval 0 to 20 km on a vertical fault is not excluded at the 90 percent confidence limit. Thus the geodetic data support the conclusions of Rogers and Hasegawa that the 1946 earthquake was caused by right-lateral, normal slip on the Beaufort Range fault in the vicinity of Forbidden Plateau, central Vancouver Island.

5. A 15-station geodetic control network extending 10 km north and 40 km south of the Motagua fault in Guatemala near the epicenter of the February 4, 1976 earthquake (M_S=7.5) was reobserved in 1978. The initial first-order triangulation was observed in two parts: the southern border arc completed in 1935 and the fault crossing Motagua Valley arc completed in 1953. The deformation indicated by angle changes between the combined 1935-53 survey and the 1978 trilateration survey was used to determine fault slip assuming a simple dislocation model. The model fault was divided into three successively deeper sections. The inversion predicts average left lateral slip of nearly 1 m near the surface increasing to 2 m in the 5-15 km section, and becoming undetermined at greater depths. The surface slip is similar to that measured by Plafker (1976), and the increased slip at depth can be used to

explain the afterslip discussed by Bucknam (1978). The seismic moment predicted by the 0-15 km displacements over the 250 km long fault break is 2.2 ± 0.5 x 10^{27} dyne cm and agrees with independent estimates obtained from long-period seismic surface-waves by Kanamori and Stewart (1978).

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MWDM STRAIN MEASUREMENTS IN CENTRAL CALIFORNIA

Contract No. 14-08-0001-15877

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SUMMARY

The multiwavelength distance-measuring (MWDM) instrument developed at the Applied Physics Laboratory of the University of Washington has operated in central California near Hollister since September 1975. Length measurements of nine lines radiating from the central instrument site have been conducted on a daily basis for the past 1100 days. The instrument has demonstrated a capability to make measurements to a precision of 1 part in 10^7 over baselines 1 km to 10 km in length.

The results of the last 6 months generally substantiate the interpretation of earlier MWDM data. The data lead to four important conclusions, which can be summarized as follows:

(1) The long-term (years) MWDM data suggest that crustal deformation in the region is characterized by a rigid block model.

(2) The intermediate-term (weeks) changes in line length show that the movement of these rigid blocks occurs in well-defined episodes interspersed with periods of relative quiescence.

(3) The MWDM data suggest that these episodic displacements do <u>not</u> necessarily occur simultaneously on adjacent blocks when an intervening fault zone is present.

(4) The short-term (hours) data indicate that surface creep events probably do not extend deeper than 1 km in the region.

These four conclusions can be explained by a simple rigid-block model overlain by a thin surface layer. The strike-slip movement of the rigid blocks eventually loads the overlying layer to failure. It is this failure that is represented by the surface creep event detected by creepmeters. The deeper, rigid-block behavior and the nonsimultaneous movement of the blocks imply that the Calaveras fault near Hollister is a very low-stress system.

Many of the small earthquakes that occur in the region may result from small patches of more difficult slip on the fault plane that are loaded to failure by the larger-scale aseismic episodic slip. If this is true, prediction of a specific small earthquake may be more difficult than expected. It might be more appropriate to issue forecasts of increased seismic risk.

The current effort has identified two areas where further study is needed. The first concerns the MWDM array in Hollister. Much of the analysis of the MWDM data has assumed that line-length changes are due to movement parallel to the Calaveras fault. This assumption is predicated on the results of simple strain models and on the work of J.C. Savage and his co-workers. We are currently working to make the MWDM instrument more portable, thereby enabling periodic occupation of other stations in the MWDM array with the instrument. This will allow the direct determination of the horizontal displacement field. An additional incentive for this increased portability will be the capability to respond quickly to a large seismic event in some other region.

The second area where further study is indicated is in benchmark stability. Before widespread use of the MWDM technique is begun, we need to establish the best design of, and the proper installation and site selection criteria for, the benchmarks that will be used in future MWDM measurements.

TECHNICAL REPORT, ANNUAL

DRY TILT AND NEARFIELD GEODETIC INVESTIGATIONS OF CRUSTAL MOVEMENTS, SOUTHERN CALIFORNIA

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Effective Date of Grant: 1 October 1977
Grant Expiration Date: 30 September 1978
Date of this Report: 31 October 1978

REPORT SUMMARY

This report presents the results of two years of nearfield geodetic studies in southern California. The purpose of these studies is to establish and monitor a variety of geodetic arrays that measure surficial crustal deformation, if any, which may precede damaging earthquakes. The kind and type of geodetic arrays are similar to those utilized by the Chinese in their earthquake prediction program, and our arrays are located near faults in California which are generally considered to be active and imminently capable of generating a major earthquake, such as the San Andreas fault near Palmdale, as well as lesser potentially active faults elsewhere in southern California.

The geodetic arrays are of four types as summarized below together with the number of arrays which we presently monitor:

1) Dry tilt arrays (43)
2) Short precision level lines (15)
3) Leveled alignment arrays (2)
4) Small aperture trilateration arrays (11)

The dry tilt arrays are resurveyed monthly, the short precision level lines are resurveyed from one to three times annually, the leveled alignment arrays are resurveyed from two to four times annually, and the trilateration arrays either have been resurveyed annually to date or have been established only very recently.

During the two years of study, this investigation has been a negative experiment. We have observed no anomalies or trends of any kind in the data which would have led us to suspect we trapped an earthquake precursor, and indeed, no noteworthy earthquakes occurred within one source dimension of any of our arrays. The Santa Barbara and Goleta earthquake of 13 August 1978 (M=5.7) was a submarine earthquake, the epicenter of which was about 10 km from the nearest of our several short precision level lines in the Santa Barbara area. Resurveys of these lines after the earthquake show no significant changes whatsoever relative to as many as five surveys since 1970.

This report has five appendices containing location, geometry and tilt data for all the dry tilt arrays and EDM arrays. Appendix VI is an analysis of the precision and accuracy of the Hewlett-Packard Model 3808 distance meter. The analysis was done by UCSB graduate student Richard Terres.

PERIODIC GRAVITY OBSERVATIONS IN SOUTHERN CALIFORNIA

By

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Earth Science & Engineering is periodically observing gravity in Southern California under two contracts sponsored by the U.S.G.S. The first contract is for the semi-annual observation on a network of gravity stations across the San Jacinto Fault and a small portion of the San Andreas Fault. The network has been expanded to 130 stations and now crosses the Elsinore Fault. Three years of observations have been completed. The second contract is for the monthly observation of a network of 86 gravity stations along the San Andreas Fault from the Salton Sea area northwestward to the Carrizo Plain. Twenty two months of observations have been completed. Two LaCoste and Romberg Model D Microgal gravimeters are used for all observations. Their performance has been compared to Model G geodetic gravimeters. Some large changes in gravity have occured at stations atop ground water masses that changed during the drought of summer 1977 and heavy recharge of the winter of 1978. Some significant gravity changes have occured where ground water could not be the cause. The changes must be attributed to vertical tectonic movement.

CONTINUOUS GRAVITY MEASUREMENTS IN THE REGION OF THE PALMDALE UPLIFT

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University of California, San Diego

A superconducting gravimeter was installed at Lytle Creek in July 1978 along with one of our computer controlled data systems. There have been a number of interruptions of the data since then so that no reliable estimate of the long term drift at the site can be made as yet. However, the noise level in the frequency band of the normal modes of the earth is lower than at any other location where we have operated. In addition to the instrument at Lytle Creek, we now have instruments operating at Otay Mountain (San Diego), Piñon Flat, and Boulder, Colorado. A fifth instrument will be installed at Goddard Space Flight Center in Maryland on November 1 and a sixth at The Geysers (California) later in November.

The data system is fully operational with two-way telephone communications to the minicomputer in our laboratory. At current sampling rates, 25 hours of data can be stored in the memory of the LSI-11 computer and transmitted by telephone for immediate display on a CRT terminal. Thus the status of the instrument can be checked at any time by calling from the lab. The data is also recorded on magnetic cassettes for retrieval whenever the site is visited. If all of the bugs are now out of the system, this will be about every 2 months when the liquid helium is replenished.

The delay in deployment of the instruments last year was due to a noise problem that had not previously been encountered. Ultimately it was traced to the superconducting magnetic shield and was a consequence of the use of steel Dewars which we had not used previously. With that problem solved, assembly and deployment of the instruments has speeded up considerably.

At the same time we have continued our study of the long term drift of the instruments which have been operated at Pinon Flat. We have now analyzed three years of data from an early version of the instrument without some additional stabilizing coils which are now in use. An additional 2 years of data from an instrument with stabilizing coils is now being analyzed. The first 1 1/2 years of the record showed a linear drift, determined by least squares fit, of 139 μgal/year. At the end of this period the instrument was shut down for 2 weeks. When it was reinstalled it was "annealed" by raising the temperature and the magnetic field above the final operating values. For the subsequent 1 1/2 year the least squares fit linear drift was 4.8 μgal/year. The figure shows the residual signal from the full three years after removal of tides, atmospheric effects, and the above stated linear drifts. The peak-to-peak variations are approximately 10 μgal and take place over periods of 3 to 5 months. Thus an apparent linear drift of 4.8 μgal/year over 18 months is probably a consequence of these 3 to 5 month non-monotonic variations.

We have been unable, as yet, to perform an adequate test of drift by running two instruments side-by-side, but the short test we did make in 1976 indicated that variations on the scale shown in the figure are probably true gravity variations or else tilt of the gravimeter pier. Thus a determination of the gravity variation at Lytle Creek should be at least at the 10 μgal level as shown in the figure, and perhaps better if tilt is monitored more closely. A comparison of the six instruments operating during the coming year will also provide important information about drift rates.

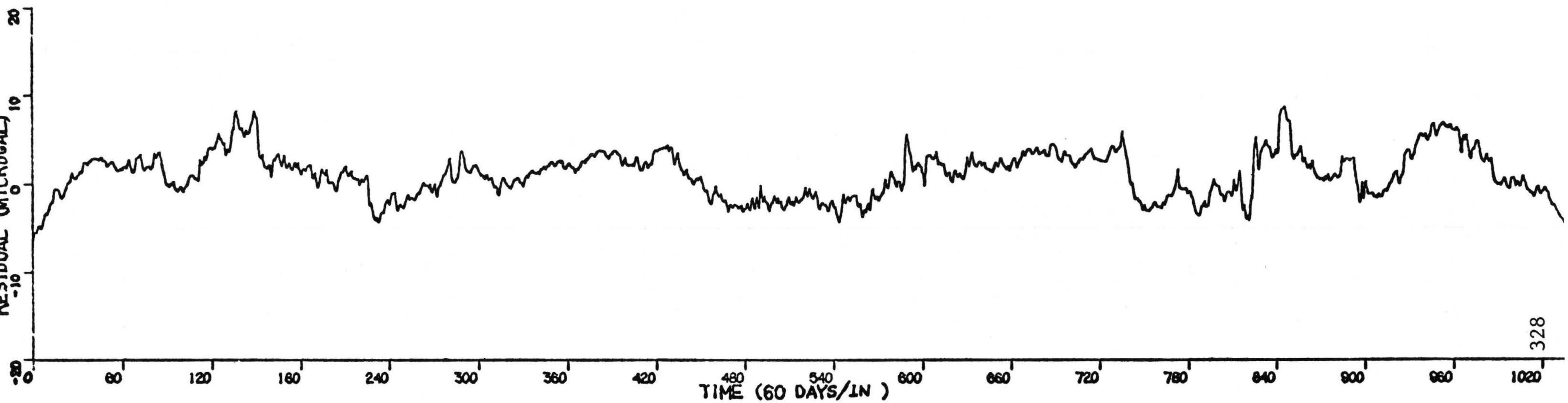
RESIDUAL (MICROGAL)
20
10
0
-10
-20
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
1020
TIME (60 DAYS/IN)

Figure 1

Southern California Gravity Surveys and Analysis

8-9730-01034

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Investigations

1. Data from a detailed calibration range in southern California were analyzed to determine non-linear calibration functions for gravimeters used during the Southern California Releveling Project. Sixteen LaCoste and Romberg G-meters and three LaCoste and Romberg D-meters were examined.

2. Processing of gravity data collected during the Southern California Releveling Project is continuing. Gravity data collected in southern California during 1976 and 1977 have been reprocessed using detailed gravimeter calibration information obtained from the calibration range.

3. Gravity was remeasured along a 25-station east-west profile across Owens Valley from Whitney Portal to the Inyo Mountains. The profile crosses the surface trace of the fault that slipped during the 1872 Lone Pine earthquake. Previous gravity and level surveys were conducted during October 1974. A level survey also was conducted concurrent with the 1978 gravity survey.

Results

1. Periodic non-linearities were detected in the calibration functions of approximately half of the model G-gravimeters tested. The periodicities had predominant wavelengths of approximately 75 and 37.5 mGals. Of the gravimeters that displayed these periodicities, most showed peak-trough amplitudes in the range 20-40 μGal with the largest being about 70 μGal. Some evidence also was found for the presence of non-periodic non-linearities in the calibration functions.

2. Application of the detailed calibration information to data from repeat surveys made with gravimeter G-425 resulted in an average reduction of about 25 percent in the magnitude of apparent gravity changes between two surveys.

Reports

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World-Wide Earthquake Research Database

8-9930-02104

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Investigations

The main goal of this project is to provide up-to-date information which will facilitate research on earthquakes. Three major topics are now under investigation:

1. Feasability study of the establishment of a seismograph library of significant earthquakes (especially those before 1963),
2. Organize and maintain a bibliographic database and retrieval system on current earthquake literature, and
3. Compile an accurate catalog of worldwide earthquakes.

Results

Seismogram Library. Under contract from this project, the National Geophysical and Solar-Terrestrial Data Center, NOAA, has completed the investigation of a suitable portable photocopying system for filming historical seismograms. In fiscal year 1979, this subproject will be directly contracted to NOAA by the Branch of Global Seismology at Golden. A scientific advisory group has been organized by the International Association of Seismology and Physics of the Earth to select significant earthquakes and critical seismic stations.

Bibliographic Database and Retrieval System. Since the last Semi-Annual Summaries, six additional monthly issues of Index to Current Earthquake Literature have been distributed. Because of a drastic budget reduction of this project in FY 79, this subproject was terminated in October 1978.

Earthquake Catalogs. Steady progress has been made in the past months in compiling various earthquake catalogs. We have also begun an investigation of preinstrumental earthquakes. This subproject is being carried out jointly with Wilbur Rinehart of NGSDC, NOAA.

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NOISE REDUCTION TECHNIQUES FOR TECTONOMAGNETIC STUDIES

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Grant No. 14-08-0001-G-519

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Differential measurements of the geomagnetic field in a non-seismic zone (Colorado) have been made for several years[1-3] using narrow line rubidium magnetometers (NLMs). The accuracy recently was improved[3] to 0.01 γ. The initial measurements were made with two sites 12 km apart on a roughly EW baseline. Some additional measurements were made with one additional site located either 15 km south of one of the first two to give two orthogonal baselines or 12 km east to give three colinear and equally spaced sites.[3]

Data from these measurements was analysed previously[1-3] using two techniques to reduce the geomagnetic noise to below 0.1 γ. These techniques were based on: (1) transfer functions from vector field components to simple total field differences; and (2) second differences for three colinear sites. Method (2) was applied to only a very short period of data.

Under this grant we have accumulated considerably more data on the three colinear sites, and have made substantial progress in analysing the data. In particular, a third new analysis technique was developed: (3) the use of a transfer function between simple differences for three colinear sites. This method corresponds to taking an unequally weighted second difference, with the weights depending on frequency.

Method (2) is easy to use since it does not involve cross-spectral analysis, but method (3) is more efficient. Residual noise for our three colinear sites was reduced to 0.029γ rms for one week of data (12 min averages) using method (3).[4] The transfer function used in this analysis was derived from separate data, which demonstrates stationarity. The method is well suited for analysis of array data from total field instruments, since vector data are not required. However, the method removes large scale total field gradients only. It does not reduce noise due to: (a) susceptibility differences between sites; (b) differences of magnetic field direction between sites; (c) local currents induced by ionospheric or magnetospheric sources. Method (1) should be effective in removing noise from these sources. Residual noise was reduced to 0.035γ rms for one week of simple differences (12 min averages) using method (1), and the residual of 40 days of five-day averages was 0.015γ rms.[4]

Analysis of USGS proton magnetometer data from central California[5] has begun. Method (3) was used to reduce the noise to 0.15γ rms for 37 days of data (1 hour averages) from 3 stations in California. We are now obtaining vector component data from the Castle Rock Observatory (1975) which we need to derive the transfer functions used in method (1).

Simple differences of the proton magnetometer data from California have noise levels which are an order of magnitude larger than the NLM data from Colorado (1 minute to 1 month periods). While the difference in noise level probably is due mainly to differences in ground conductivity structure and/or susceptibility, a check on the reliability of the time-averaged proton magnetometer data below the 0.25γ counting quantization level seems desirable. Thus operation of proton and rubidium magnetometers at the same site in Colorado is being considered in order to rule out systematic errors due to instrumental differences.

The potential for highly sensitive and stable component field measurements using superconducting magnetometers (SQUIDs) is also being studied. The sum of the vector components measured by the SQUID is compared to NLM total field measurements, which provide a 0.01γ standard. This study is being performed jointly with Frank Frischknecht (USGS, Denver) who is providing occasional use of the SQUID.

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MAGNETOMETER ARRAY 1978

by

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SUMMARY

Three sites near the San Andreas fault have been equipped with Geometrics G-816 magnetometers and are recording one-minute averages of the magnetic field intensity. The sites are located at Reservoir Summit, Tumble Inn, and Kelly Ranch, as shown in Figure 1. Additional sites are being installed at Quail Lake and at "B. Smith." Data are recorded on Memodyne tape cassettes for periodic pickup. When all three sites are operating normally, the rms deviations of one-minute station averages from the array average are about 0.5 nT. Some of this variation results from pollution of the array average by relatively noisy data from one site and can be substantially reduced on using a weighted mean of the station values to form the array average (formation of station differences is a special case of this procedure).

We operated four Geometrics G-816 magnetometers within 100 m of each other for a period of three weeks in an orange grove adjacent to the UCLA campus. The site proved to be magnetically noisy. One of the instruments had a rather high failure rate, but the agreement among the other instruments indicated that rms errors due to instrumental effects and very local site variations amount to about 1 nT for one-minute averages of the field intensity.

We have experienced a large number of malfunctions caused by minor design faults and aggravated by heavy rainfall. The design problems have been corrected (we think) and we have submitted a formal request for more moderate rainfall in the future.

We have completed the design and construction of a fluxgate (vector) magnetometer for installation at the Quail Lake site. A second fluxgate is being constructed for the B. Smith site. Before field installation, the instruments are being carefully tested in the laboratory and will be tested against a cryogenic magnetometer as part of a cooperative effort between USC and UCLA. The fluxgates are to be mounted on platforms equipped with tiltmeters to monitor rotation of the magnetometer axes with respect to those of the earth's field. The magnetometers are field aligned with Z parallel to the earth's main field, X north in the dipole meridian, and Y positive to the east. The dynamic range of the basic magnetometers is ± 256 nT. The Z axis

is provided with a bidirectional offset field generator to extend its dynamic range. Each basic magnetometer has a bandwidth of 32 Hz and samples the field 64 times per second. The resolution is 1/8 nT. One-second averages are then formed with resolution of 1/128 nT. Successive one-minute averages are recorded on a cassette recorder with hourly averages from the two tiltmeters, the Z offset generator, and several temperature sensors and voltage reference points.

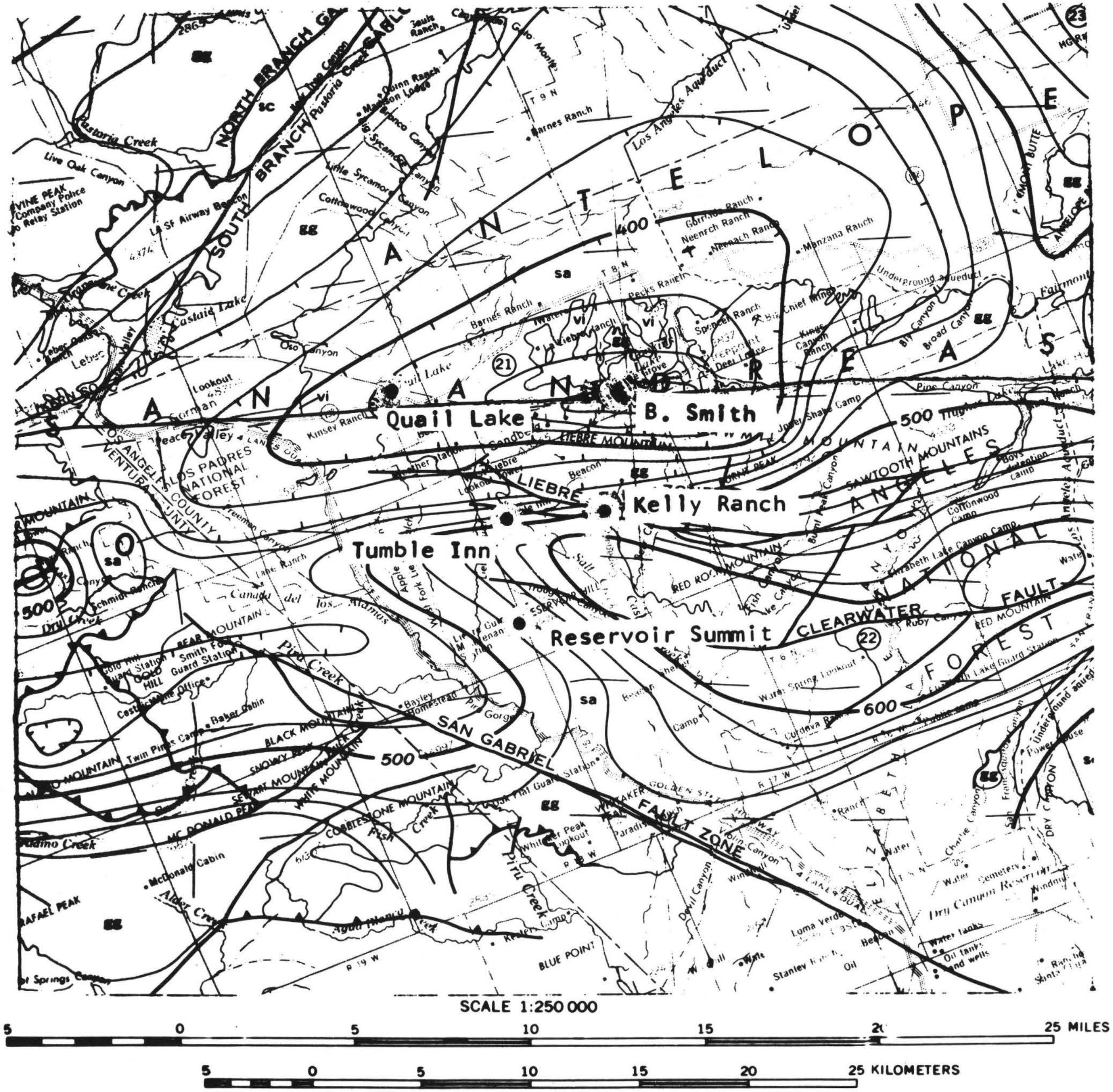
We have continued to monitor apparent resistivity by active measurements across the San Andreas Fault near Lake Hughes. Resistivity values were constant to within 1% for about 8 months, then fell by 6% during the heavy rains beginning December 1977. The resistivity has only partially recovered to its former value, indicating that the rainfall effect has a relaxation time of at least one year.

Publication under this grant:

Searls, Craig, K. A. Poehls, D. D. Jackson and E. M. Wescott. Changes in crustal resistivity near Palmdale, California. Submitted to Geophys. Res. Lett., 1978.

P.B.5.

Figure 1



Quail Lake
B. Smith
Kelly Ranch
Tumble Inn
Reservoir Summit
A N T E L O P E
S A N A N D R E A S
SAN GABRIEL FAULT ZONE
CLEARWATER FAULT
400
500
600
SCALE 1:250 000
5 0 5 10 15 20 25 MILES
5 0 5 10 15 20 25 KILOMETERS

Magnetic Observations Related to Earthquake Predictions

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The purpose of this work is to study the changes in magnetic properties of rocks brought about by the application of stress. We have reported previously (Tech. Rep., vol. IV) that the magnetic response to stress is dependent upon the type of magnetization the sample is carrying. For example, uniaxial compression to failure of polycrystalline magnetite at room temperature gives rise to strong demagnetization if the initial magnetization is a IRMs, but a large anomalous increase in remanent moment is observed with major rotation, if the initial magnetization is a TRM. Intermediate effects were seen with magnetite after AF demagnetization and stressing in zero field. We have investigated this further by introducing the effects of annealing. Magnetite samples annealed at 600^{o}C for one hour and cooled to room temperature in five hours, were given a IRMs and then compressed in zero field. The initial decrease in intensity of magnetization was followed by a comparable increase at higher stresses. This behavior is somewhat intermediate between that seen with samples carrying a TRM and samples carrying a IRMs without anneal. This indicates that a release of residual stress drastically alters the stress response, and is at least partially responsible for the anomalous increase in intensity previously reported. We are now conducting more experiments carefully controlling annealing conditions.

In an attempt to understand the various observed magnetic responses to stress, we initiated (Tech. Rep., vo. V) a study of the irreversible changes in magnetic properties caused by stress, or magnetic stress after effects. Samples were stressed to different pressures and their magnetic properties measured after the stress was released. The effect is to harden the initial remanence by demagnetizing the soft component, and to substantially increase the coercive force with increasing stress. This shows directly that magnetic and mechanical hardnesses vary in similar fashions. Parameters such as Hrc and Js did not show a continuous trend with increasing pre-stress, and no significant conclusions about their behavior can be reached at this point. The susceptibility after effect was also investigated, and although this is small (1 to 2% of the initial value), it seems significant. For all samples the susceptibility perpendicular to the axis of compression decreased with increasing pre-stress. The susceptibility parallel to compression decreased with increasing pre-stress for a sample initially carrying a TRM, was constant for a sample carrying a IRMs, and increased for a sample previously AF demagnetized as well as for a sample annealed and carrying a IRMs. This led to a detailed study of the dependence of susceptibility upon the state of remanence for various materials (polycrystalline magnetite, single domain titanomagnetite x = 0.4, pyrrhotite).

The differences between susceptibilities for the various states of remanence are small (1 to 2%) but very reproducible. Susceptibility varies smoothly for transition from one state of remanence to another. Two main groups of susceptibility values can be distinguished. Samples carrying IRMs, ARM, or samples which have been AF demagnetized comprise one group. Samples carrying TRM or thermally demagnetized form a second. The latter show systematically higher susceptibilities than the former by a few percent. The distinction within each group is less clear, and some overlap exists between various states. This seems to be dependent upon the type of material and grain size. The distinction between the two groups of remanent magnetization states suggests that the domain configurations of IRMs and AF demagnetization are significantly different from such thermally activated patterns as those of TRM or thermal demagnetization. Moreover, since the stress response of these domain patterns also varies, we begin to see important aspects of the domain patterns which determine both reversible susceptibility and the stress response.

The anomalous increase in magnetization which was observed when samples carrying weak field remanence were stressed is potentially important for earthquake prediction if it persists under conditions prevailing in the earth's crust. We reported (Tech. Rep., vol. V) that it is at least partially reversible under cyclic compression, but the effects of confining pressure and temperature remain to be demonstrated. A pressure vessel allowing for simultaneous application of uniaxial and confining pressure inside the magnetometer has been constructed in collaboration with S. Pike (USC), to study these effects. This instrument has now been tested on the bench and inside the magnetometer, and stress experiments will be started in a matter of days. Measurements on a selection of rocks from formations along the San Andreas fault will be made in collaboration with S. Pike. From our previous results (Tech. Rep., vol. V) we know that multi-domain ferromagnetic carriers are the best stress transducers, and that single domain particles show only a small response to stress, if any. Rock magnetism properties have been measured for all the samples to be tested, and only a few are expected to show a significant magnetic response to stress. If this is verified by experiments, it should provide a very good test of our previous results, as well as establish which rocks are potential transducers of the seismomagnetic effect. We have additional samples from rock units along the San Andreas, provided by M. Johnston (USGS), and we intend to compile a complete catalog of magnetic stress sensitivities for various rocks along the fault. Further experiments with polycrystalline magnetite will also be conducted in a very near future combining uniaxial and confining pressure.

INVESTIGATION OF THE PALMDALE UPLIFT USING DIFFERENTIAL MAGNETIC FIELD MONITORING OF TECTONIC STRESS

Contract #14-08-0001-G-379
Floyd J. Williams, Principal Investigator
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This research project was initiated in July, 1973 with the establishment of 10 magnetometer sites along the San Jacinto fault zone from Pearblossom to Anza. Since then coverage has been expanded until at present we have a 2-dimensional array consisting of 51 sites. The San Andreas fault is monitored from near its junction with the Garlock on the NW to the Indio Hills on the SE. Several other active faults located around the eastern and northern flanks of the San Bernardino Mountains are being monitored as well.

The method involves taking simultaneous total magnetic field measurements at adjacent sites located from 10 to 15 km apart in the array. Utilizing two proton precession magnetometers with quarter-gamma digital readout, we take readings at the two sites over an identical 10-minute interval of time. Mean values of the data sets are computed and differenced. The variation of this difference of means becomes, via the piezomagnetic effect, an indicator of tectonic stress change in the crust beneath the site pair.

A better understanding of measurement error has gradually emerged as we have analyzed standard deviations, made repeat experiments, and looped sequences of sites so that closure error could be determined. For 125 data sets of 76 observations each, the mean of the standard deviations is 0.6 gammas. Closure error on loops of sites is usually less than 0.25 gammas per site.

The most significant result obtained is the correspondence in time and place between the partial collapse of the Southern California Uplift as defined by differential leveling and a 10 gamma anomalous field that was measured from late 1973 to 1976. The anomaly amplitude has slowly decreased with time since its peak in 1976. The observed magnetic changes are believed to be due to changes in crustal stress that result in corresponding changes in the induced and remanent magnetization. Smaller anomalies probably associated with magnitude 4.4 and 4.2 earthquakes in an area N of San Fernando, have also been observed.

Some of the magnetic changes observed in the past at certain sites is now understood to be due to stream erosion resulting in sediment removal and redistribution. If a site is destroyed or if the magnetic field near a site is modified by artificial means, a new site is established. When an earthquake occurs, site-pairs in the epicentral area are promptly measured. With increasing experience and the occurrence of earthquakes within the array, the range of detectability of the method will be established for varying magnitudes of earthquakes.

Two to three surveys are carried out each year across the entire array. The method is a versatile, inexpensive, and effective way of monitoring tectonic stress change across approximately 7,000 square miles of southern California.

CORNELL UNIVERSITY

Progress Report - Arthur F. Kuckes

Grant No. 14-08-0001-G-521, "Application of a Controlled Source Electromagnetic Method to a Search for Changes in Electrical Conductivity in the Earth's Crust"

We have just completed an EM induction survey in the Paicines area using an electric dipole source aligned parallel to the fault zone. Horizontal and vertical magnetic fields and horizontal electric fields were measured at a series of sites running roughly perpendicular to the fault zone and extending out to nearly 25km from the dipole source. The source was driven with a square wave signal 1 and .1 HZ.

Currently, our effort is directed toward analyzing this set of data and fitting the data to appropriate conductivity models.

In the course of taking this data, we have gotten a series of 3 measurements at one site over about a month's time during which there were several small earthquakes ($M \approx 3.0$). We will check this data for temporal changes in the fields at this site. By calibrating our equipment several times during the months of collecting data, we know that the variations in the response of the sensing equipment is $\approx 3\%$ so that any temporal changes greater than this value may be significant.

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Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

High Sensitivity Monitoring of Resistivity and Self-Potential Variations in the Palmdale and Hollister Areas for Earthquake Prediction Studies

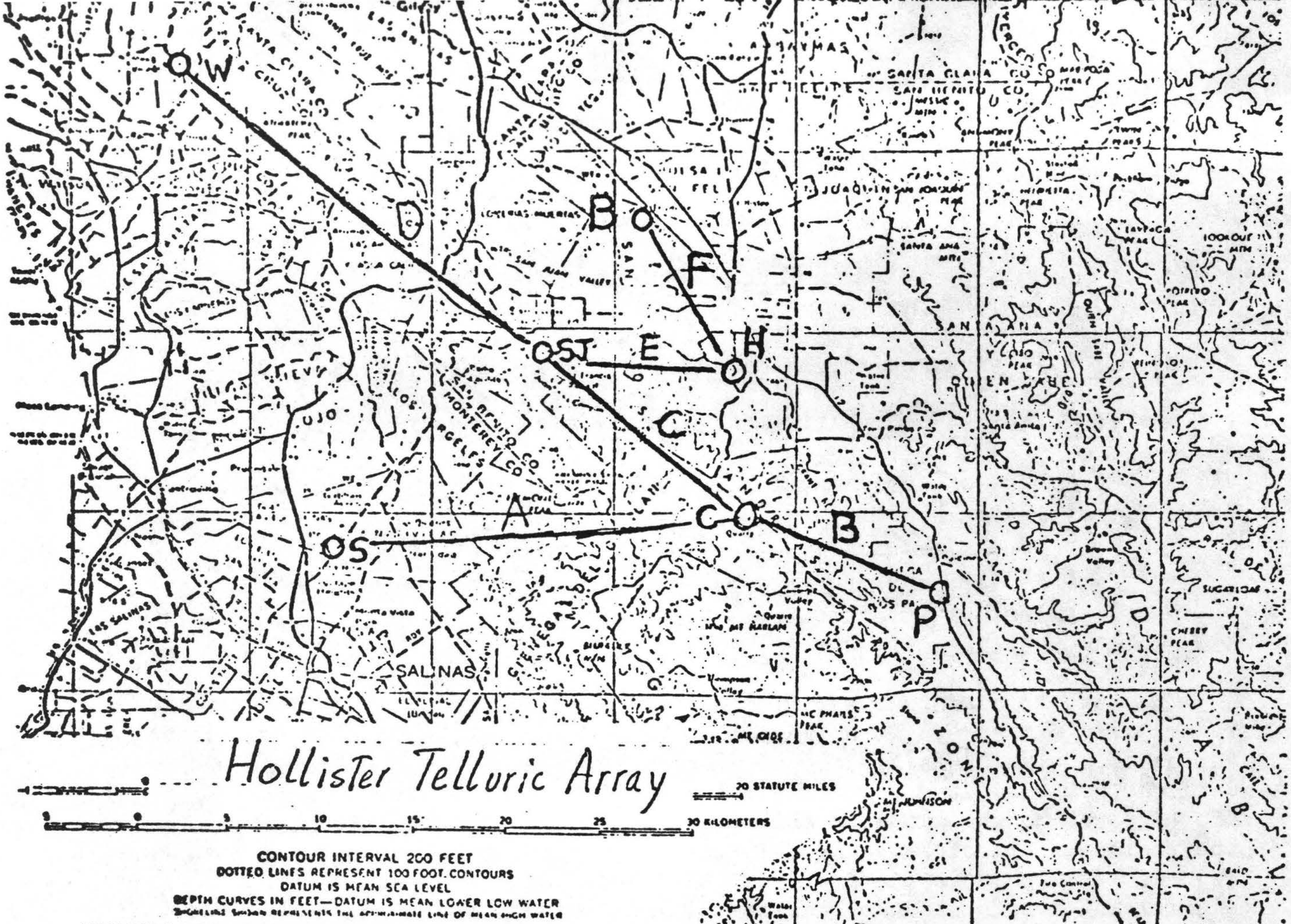
Summary of Semi-Annual Technical Report, April 1978 - October 1978

Contract No. 14-08-0001-16724

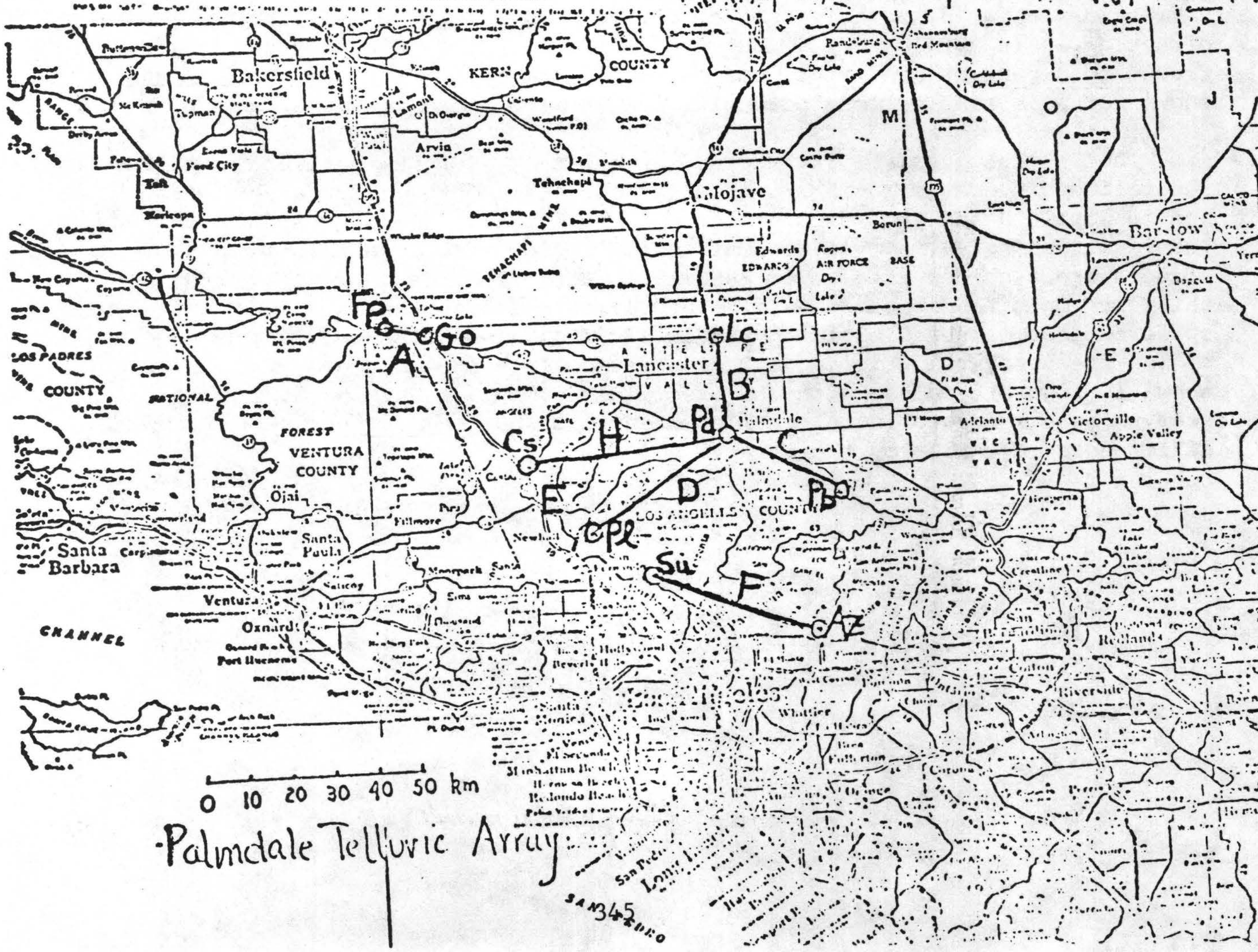
Principal Investigators: Theodore R. Madden and M. Nafi Toksöz

We have no significant resistivity or self potential variations to report from our arrays in Hollister and Palmdale. The Hollister resistivity variation analysis was hindered by paper slippage on the recorders and the data was not digitized for correlation analysis. This also prevented us from separating the two independent contributions to the telluric field in the residuals all of which greatly decreases the sensitivity of the results. The results are shown in figure 2. We do not consider these variations significant because of the difficulties mentioned above. The self potential variations assigned to individual electrode sites are shown in figure 3. The offset on SJ in April and May and on H in June, July, and August can be traced to a particular circuit board and is not real. The large variations shown for W is an electrode potential problem that must be taken care of.

The Palmdale resistivity variation results are shown in figure 4. The generalized inverse solution was modified as most of the fluctuations seemed due to dipole B and this dipole's effect was subtracted out from the results. The variations of B may reflect only digitization errors as this dipole's effects are recorded at a lower sensitivity. We shall soon be able to test this with on site digitized data. The Palmdale self potential variations also suffered from large electrode potential drifts, as well as from some aliasing of low frequency telluric cancellation residuals. The unprocessed data is shown in figure 5, along with the electrode potential contributions. The trends seem to be all due to the electrode potentials, but some actual self potential differences may exist on the array.



Hollister Telluric Array



Palmdale Telluric Array

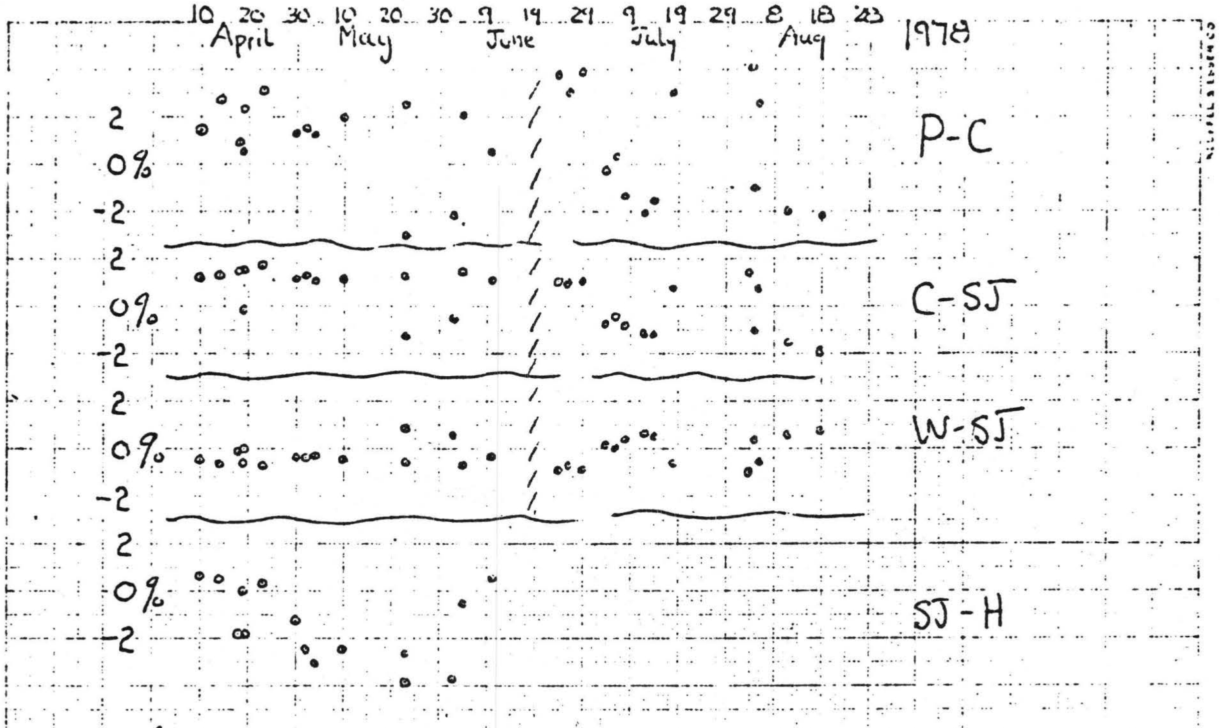


Fig 2 (Low Resolution) Resistivity Variations Hollister Array

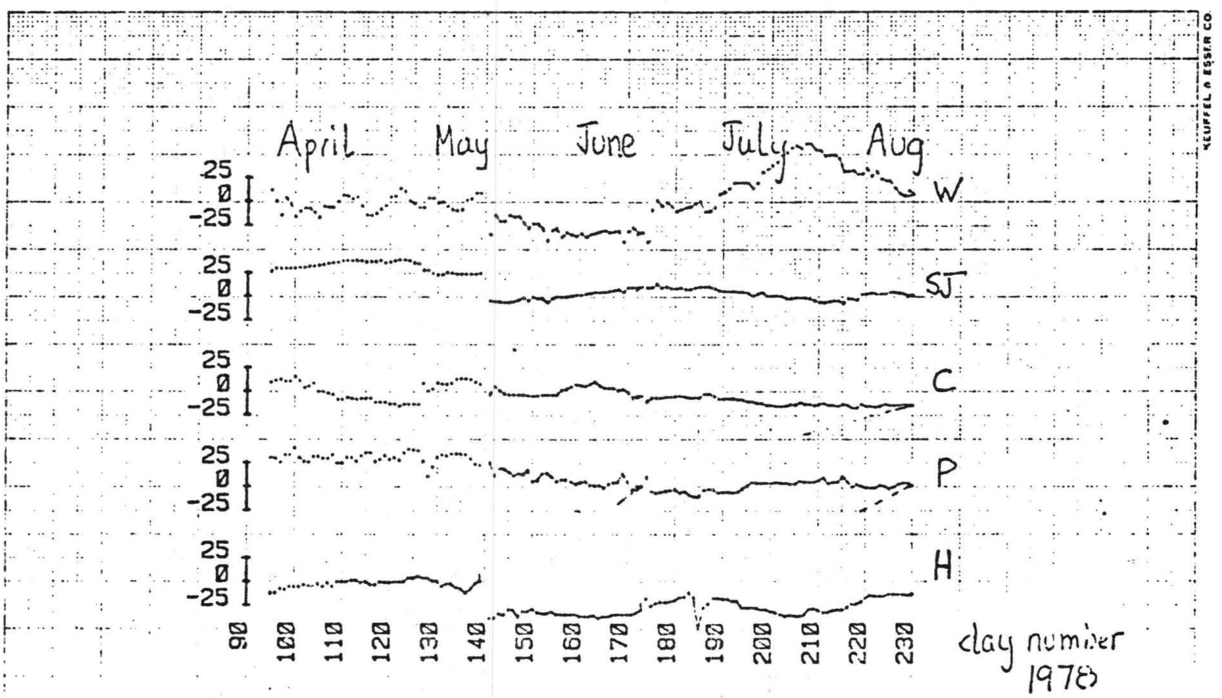


Fig 3 Self Potential Variations on Hollister Array
relative to S
from inversion of array potential residuals

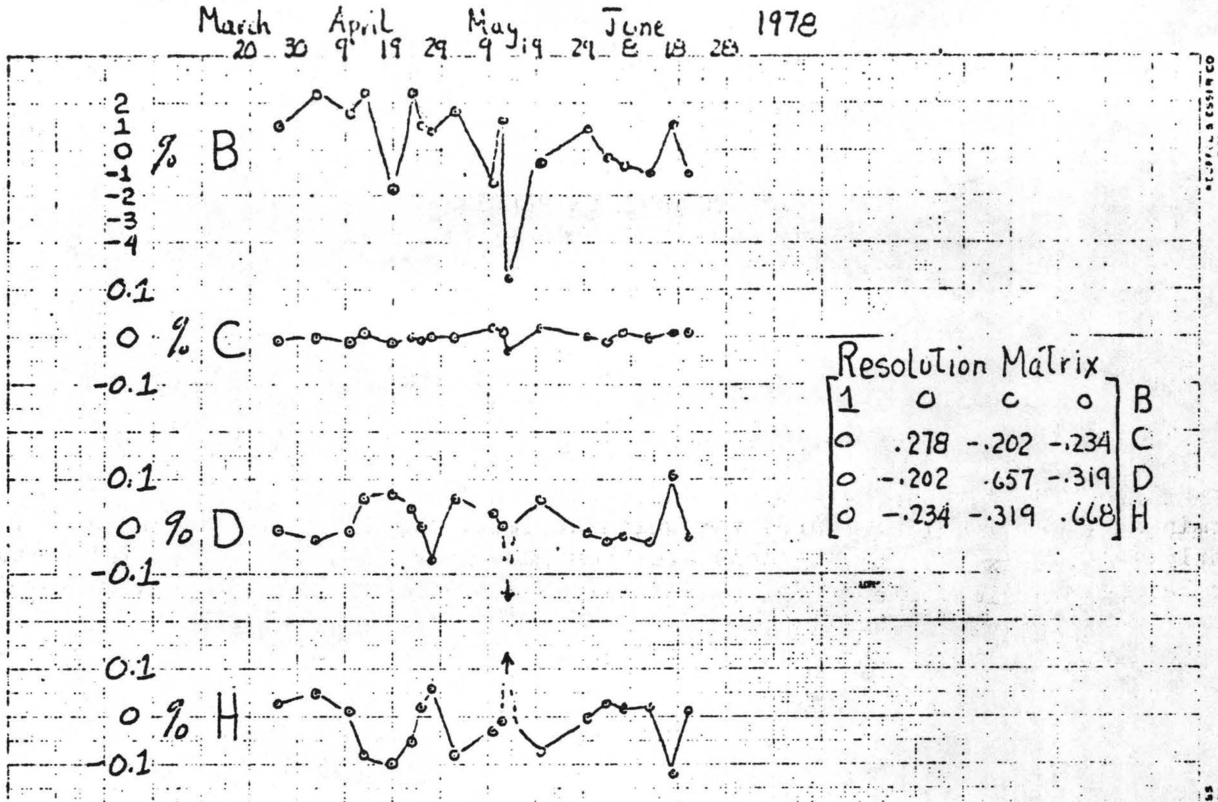
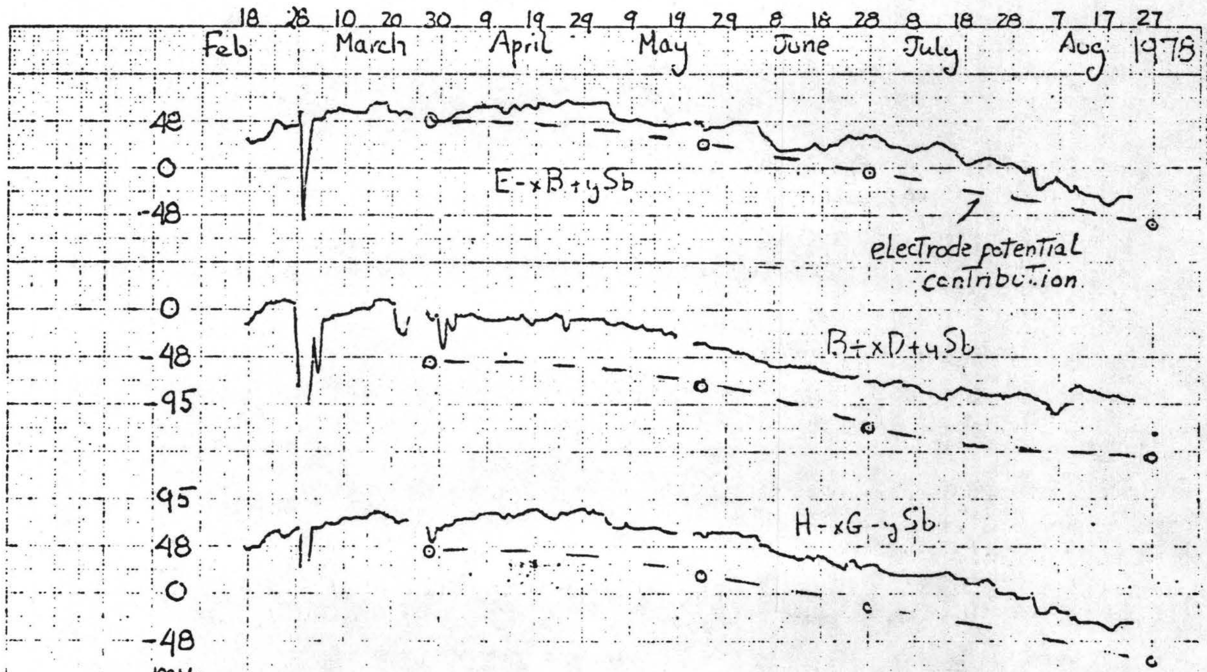


Fig 4 Resistivity Variations
Palmdale Array (assuming noise contribution to B)



Self Potential Variations Palmdale Array

Fig 5

INVESTIGATION OF RADON AND HELIUM AS POSSIBLE FLUID-PHASE PRECURSORS TO EARTHQUAKES

H. Craig, J. E. Lupton, Y. Chung,
R. M. Horowitz, and R. Poreda

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This report contains the data measured to date on the Southern and Palmdale Network in wells and hot springs. The measurements include temperature, conductivity, dissolved radon, helium, nitrogen, argon, and methane, stable isotopes (deuterium and oxygen-18) in water, radium-226 and lead-210 activities, and soil radon measurements by alpha particle track counting. N_2, Ar, and CH_4 measurements have been made at most sampling sites when significant fluctuations in helium or radon are observed. The hot spring data show that almost all the fluctuations in the springs are due to varying mixtures of a "deep component" water, which contains the He, Rn, and CH_4, and N_2 and Ar at approximately the original surface water atmospheric solubilities, with an "atmospheric component" which contains less N_2 and Ar at the higher-temperature atmospheric solubility of the surface water. Measurements of N_2, Ar, and He in a "natural" hot spring formed around a break in a deep well at CO_2 wells in the Imperial Valley show an opposite relationship--mixtures of a low concentration, highly-degassed water with an atmospheric component with <u>higher</u> N_2 and Ar concentrations, thus providing strong confirmation of the mixing model. Dissolved gases in the wells also form linear concentration arrays, but these effects are more complicated and are related to the phase separation processes in the wells. However, in both the springs and wells, normalization to N_2 or Ar provides a much more sensitive measure of helium or radon fluctuations which may correlate with seismic activity. Thus we should be able to see precursory helium and radon variations which may be associated with seismic events of considerably lower magnitude than has previously been possible.

Monitoring on the Palmdale Network ceases with this report, as the continued monitoring of this network has been transferred to USC by request of the U.S. Geological Survey. Final soil radon measurements made at La Jolla are also included in this report; we continue to install and collect the film strips, but track counting work has been transferred to Menlo Park to provide a uniform set of data in the future. A few laboratory measurements of soil radon activity are reported and compared with data from the field sites where the soil was collected. The laboratory measurements do not correlate with the observed field data, indicating that significant transfer of radon occurs in the soils at these locations (Imperial Fault).

Helium Variations in Water as a Earthquake Prediction Tool

9-9740-00382

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Investigations

To assess the usefulness of helium variations in deeply circulating natural waters as an earthquake prediction tool. This is being carried out in two stages.

1. By having volunteers and a few paid collectors mail water samples collected daily from water wells. These samples are analyzed for helium in Denver. This phase allows us to choose wells that respond to earthquakes for automated analysis.

2. Responsive wells are equipped with an automated mass spectrometer that telemeters data via satellite to Denver. This data will be received every six hours.

Results

1. Completed the construction of an underground concrete structure over the Miller well, near Gardiner, Montana to house automated helium analysis unit.

2. Construction of all but the sequencing electronics for the automated helium analysis unit is complete, and the unit has been installed at the Miller site.

3. The electronic sequencing and telemetering unit (using GOES satellite) is almost complete. We expect to install this within the next month. The complete package, including sample collection, analysis and telemetering should then be operational. We will sample once every half hour, and telemeter data every six hours.

4. Continued the collection by volunteers and helium analysis of water samples from water wells in California.

5. Upgraded collection network by dropping marginally useful collection sites and adding "better" ones.

6. Continued the helium analysis of samples from the Montana network associated with the Hebgen Lake epicenters.

Radon and Water-Wells Monitoring

8-9960-01485

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Investigations

1. Radon content of soil gas in capped shallow holes is being continuously monitored by the Track Etch method at about 80 sites along several active faults in central California (see previous reports in Volume VI, p. 258 for location of most of these stations), 35 sites in southern California (in cooperation with USC, UCSD and UCSB), 10 sites in Hawaii (with HVO) and 10 sites in Fairbanks area, Alaska (with UA).

2. Radon content of ground water has been continuously monitored since February, 1978 by a Japanese monitor at an artesian well next to the San Andreas fault in San Juan Bautista, CA (in cooperation with University of Tokyo) and at an artesian well near Banning, CA (with University of Tokyo and USC).

3. Water level is continuously recorded and several water quality parameters (temperature, salinity, conductivity, pH value) are periodically measured at 5 wells in central California.

4. Water quality and flow rate are periodically measured at two springs near Calaveras fault in San Jose, CA.

5. A weather station is maintained at Stone Canyon, CA. Weather data are collected from San Jose State University and two other weather stations.

Results

1. A magnitude 4.2 earthquake occurred on August 28, 1978 near San Jose on Calaveras fault. Radon content of soil gas at stations along the Calaveras fault between the epicenter and Hollister (see Figure 1 of the previous report for station location) showed anomalous increase, beginning about three months before the earthquake (Figure 1). This radon anomaly is similar in pattern as the ones reported previously for three earthquakes in the Hollister-Bear Valley area. However, it occurred in late summer, whereas the previous ones occurred in the winter and spring seasons, implying that the recorded changes in radon emanation may be truly tectonic in origin and are not due to seasonal effects. Prior to the earthquake, a large creep event (14 cm) was recorded by several creepmeters along the Calaveras fault near Hollister, where a two-color laser geodetic meter detected also a significantly large crustal deformation episode. To the northwest of the epicenter, radon emanation showed similar increases at stations along Hayward fault (and its extension to the north of the San Francisco Bay) but not along the continuation of the Calaveras fault (Figures 2 and 3).

2. As more radon data are collected and thus the long-term base levels better established, it becomes evident that the decreases in emanation that preceeded the anomalous increases may be a significant part of the anomaly pattern. It also becomes evident that the radon emanation in the Bay area was anomalously high at the time of the Briones Hills earthquake (magnitudes 4.3 with a magnitude 4.0 foreshock on January 8, 1977. See, for example, Figures 2 and 3). So far, the same kind of radon anomalies have been recorded for all five earthquakes of magnitude 4 and above that have occurred near the monitoring networks. No anomaly was observed, however, for the magnitude 4.6 earthquake that occurred on June 21, 1977, 10 km east of Livermore, which is relatively far away from the monitoring stations.

3. Radon emanation is relatively stable along the seismically quiescent segment of the San Andreas fault between Bodega Bay and San Juan Bautista (Figure 4), again implying a radon correlation with seismicity and the absence of seasonal effects.

4. Radon emanation recorded (with HVO) in Hawaii shows similar correlation with seismic and volcanic activities.

5. Radon emanation recorded (with UCSB) at five stations in Santa Barbara, CA showed an anomalous increase and then decrease (to as low as 1/5 of the long term average value) during a period of more than half a year before a magnitude 5.1 earthquake that occurred in the Santa Barbara channel on August 13, 1978. These changes are probably not due to the heavy rainfalls that Santa Barbara had during the last winter, since similar changes are not noticed elsewhere in southern and central California where the amount of rainfall was comparable. The difference in pattern (increase followed by decrease instead of vice versa) between this anomaly and the anomalies recorded in central California, if earthquake related, can be attributed to a difference in faulting mechanisms (thrust instead of strike-slip).

6. The two ground-water radon monitors have been in operation for eight months without any significant problem.

7. The recorded water levels are generally much affected by non-tectonic activities (rainfall, barometric pressure changes, pumping, etc.). No clear premonitory changes are seen, although coseismic vibrations are sometimes recorded.

8. Changes in one or more water-quality parameters are recorded at about the time of several larger local earthquakes.

<u>Reports</u>

King, C.-Y., 1978, Radon emanation on the San Andreas fault: Earthquake Information Bulletin, v. 10, n. 4, p. 136-138.

King, C.-Y., 1978, Radon emanation in tectonically active areas: The natural radiation environment III, in press.

King. C.-Y., 1978, Anomalous changes in radon emanation and ground water quality (Abs.): EOS (American Geophysical Union Transactions), v. 59, n. 12, in press.

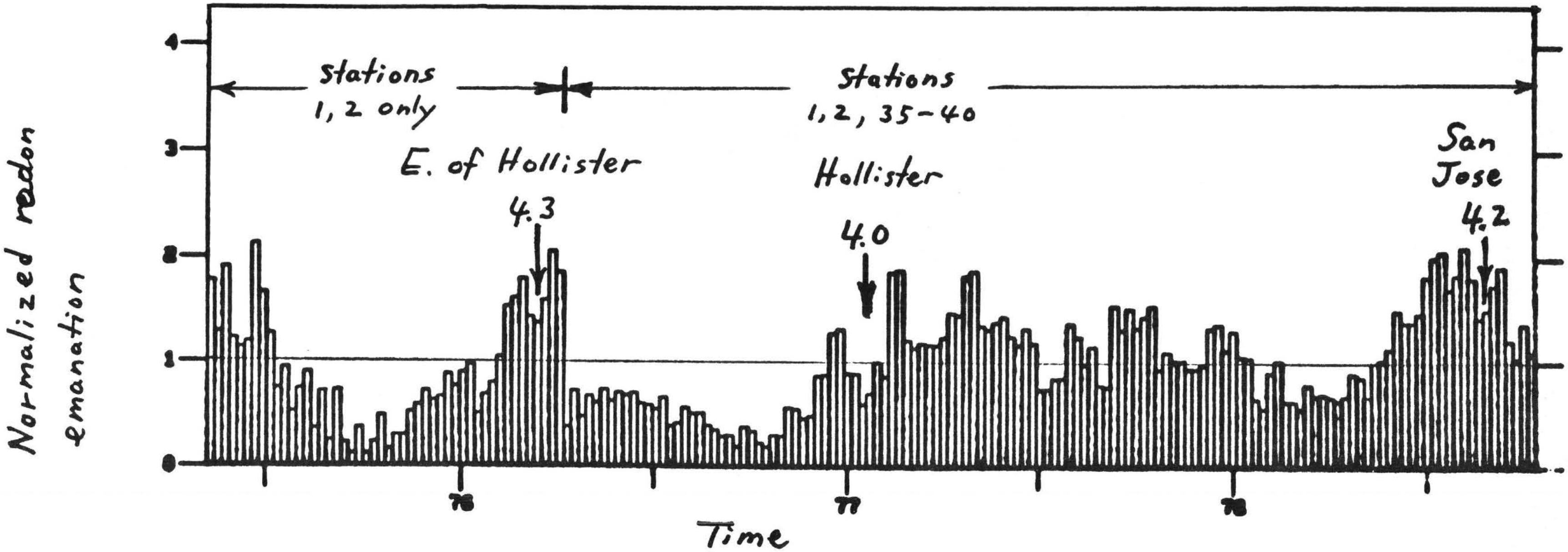
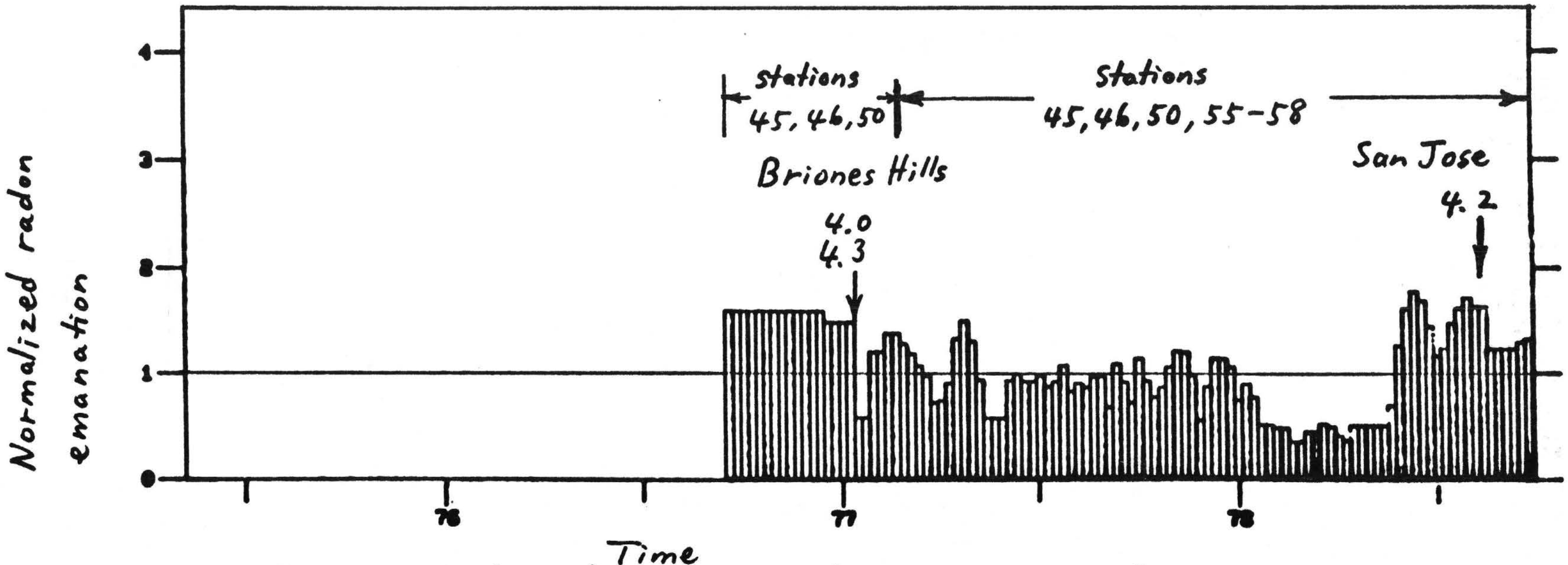


Fig. 1. Time history of radon emanation recorded by an array of 8 stations along the Calaveras fault between San Jose and Hollister. (Larger radon anomaly was recorded on San Andreas fault for the magnitude 4.0 quake, as reported earlier.)



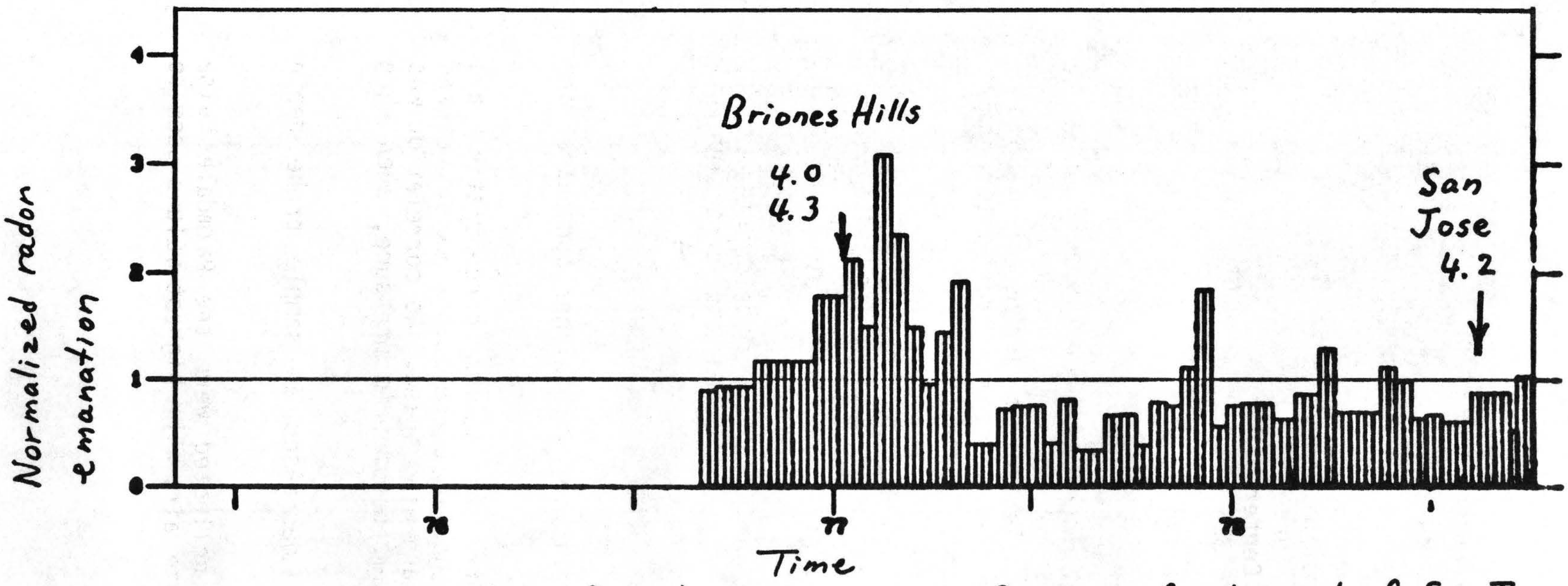


Fig. 3. Time history of radon emanation on Calaveras fault north of San Jose (stations 47-49).

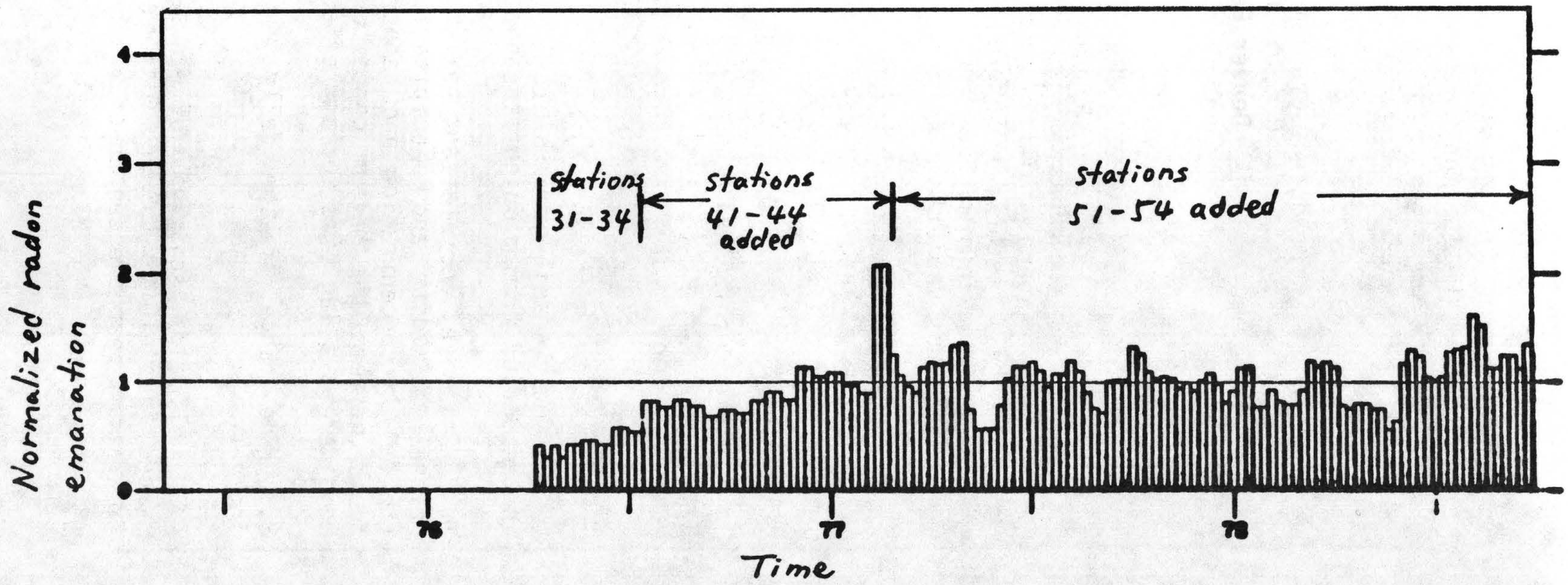


Fig. 4. Time history of radon emanation on San Andreas fault between Bodega Bay and San Juan Bautista

Helium Monitoring for Earthquake Prediction

8-9440-01376

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Investigations

1. Helium in soil gas was monitored at four localities specifically to compare the natural diurnal variations of helium in soil gas with meteorological factors. Samples were collected at depths of 0.5 to 2 meters. This information will provide the background for interpreting helium soil gas variations that may be related to earthquakes.

2. The localities were: a) at a uranium deposit in the Red Desert, Wyoming; b) at a hot springs in Idaho Springs, Colorado; c) at the San Andreas fault between San Juan Bautista and Hollister, California; d) at the Palmdale Bulge in southern California.

3. The meteorological parameters observed were: a) barometric pressure; b) air temperature; c) relative humidity; d) wind speed and direction; e) precipitation.

Results

1. Helium in soil gas exhibits a daily variation with higher concentrations in the period from midnight to noon.

2. Positive correlations exist between the helium concentration and relative himidity and precipitation. Negative correlations exist between the helium concentration and temperature and wind speed. No correlation was found between the helium concentration and barometric pressure, even when considering a lag time for any effects.

3. The range of the daily variation decreases as sample probe depth increases.

4. Helium in soil gas of 45 samples collected were the Palmdale Bulge ranged from -10 to 150 ppb with respect to air. The highest values seem to be located near the center of the bulge.

Reports

No reports.

UNIVERSITY OF SOUTHERN CALIFORNIA

Ta-liang Teng, Principal Investigator

Contract No. 14-08-0001-15875

GROUNDWATER RADON CONTENT AS AN EARTHQUAKE PRECURSOR

Research efforts to explore the usefulness of groundwater radon content as an earthquake precursor began in 1974. The work has concentrated along the locked segment of the San Andreas Fault from the San Bernardino area to Gorman, California. More than 30 sites throughout the "Southern California Uplift" are currently being monitored.

Fourteen sites, primarily hot and cold springs, deep wells and artesian wells, are monitored for groundwater radon content. Sampling is primarily at weekly intervals. No major radon anomaly has yet appeared along this locked fault segment. Smaller variations have been seen (occasionally to 50% greater than normal), but no distinct correlation with any local event has yet been made. A sample of the data is presented in Figure 1.

Twenty sites are being monitored for soil radon in cooperation with C. Y. King of the U.S.G.S. While soil radon variations have been noted before M4 earthquakes in central California, no distinct correlations have been found in southern California.

Following a visit by the Principal Investigator to the People's Republic of China in the summer of 1978, efforts to build continuous radon-counting systems for this research project have expanded. During the visit to China, it was learned that many radon anomalies are spike-like preceding earthquakes and may only be detected with continuous sampling systems. As this spike-like anomaly may be as short as one day, a weekly or monthly radon sampling program would not like capture such a precursor. The design of the U.S.C. continuous radon-counting system is an improvement on the Japanese system (Noguchi and Wakita) and the Chinese system. A Japanese continuous counting system installed in an artesian well along the Banning fault has not yet recorded any major radon anomaly.

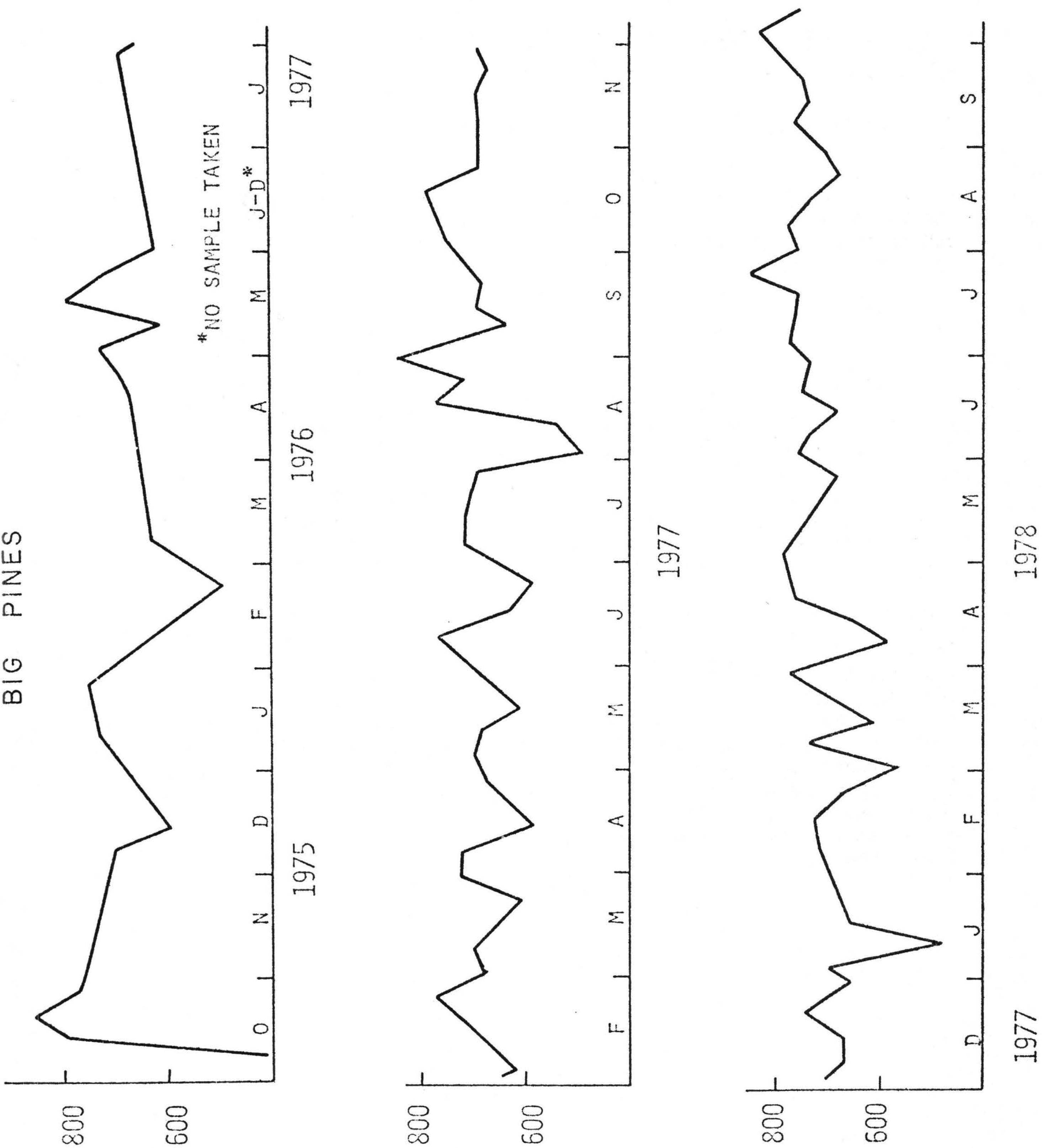
BIG PINES
*NO SAMPLE TAKEN
J-D*
DPM / KG
800
600
O N D J F M A M J
1975
1976
1977
F M A M J J A S O N
1977
D J F M A M J J A S
1977
1978

Figure 1

REPORT ON TWO YEARS OF WATER LEVEL MONITORING ALONG SAN ANDREAS AND SAN JACINTO FAULTS, SOUTHERN CALIFORNIA

Contract No. 14-08-0001-15881

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SUMMARY

Abnormal behavior of water levels in wells has been observed prior to a number of earthquakes. For instance, water-level minima have been noted in the Cienega Winery well before earthquakes on the San Andreas fault (Kovach et al, 1975). Abnormal water-level fluctuations were used in conjunction with other precursors to predict the February 4, 1975, Haicheng earthquake in northeastern China (Raleigh, 1977). That such changes should occur prior to earthquakes is not surprising. Ground water that occupies the void spaces in porous rock or alluvium can be expected to rise in wells when an aquifer is squeezed and fall when it is distended. Confined aquifers, in particular, have been found to be highly sensitive to Earth strain changes.

Water-level monitoring of abandoned water wells was begun in the Palmdale area in October 1978 with the purpose of identifying possible water-level changes premonitory to a major earthquake on the San Andreas fault. In October 1977, the monitoring program was extended southeastward along the rift zone to the Valyermo area. Currently, 26 wells are being monitored on the San Andreas either by continuous water-level recorders or on a weekly basis. In November 1977, the monitoring of water wells along the San Jacinto fault zone was initiated with the expectation of experiencing a moderate size earthquake while monitoring was in progress. Fifteen wells are currently being monitored between San Jacinto Valley and Ocotillo Wells.

Water levels are continuously monitored by eight Stevens Type F recorders and two instruments consisting of a pressure-sensitive transducer and Rustrak recorder. The Stevens recorders have proved to be extremely reliable on large diameter, perfectly vertical wells less than about 100 feet in depth. The instruments are encased in a protective housing around the well but are, nevertheless, vulnerable to vandalism. The new devices developed specifically for this project are not limited by depth or verticality of the well and are essentially vandal-proof, because the entire instrument can be inserted into the well casing equipped with a steel locking cap. To date, however, they have not proved reliable and are undergoing modification.

As the program has progressed, volunteers have been recruited to make weekly measurements of water levels, well water temperatures and rainfall. These tasks are particularly well suited to local volunteers because of their simplicity and the wide geographic area covered by the program. In general, the volunteer program has been highly successful. Weekly water-level and temperature data are displayed on computer-generated hydrographs for each well. Rainfall and earthquakes are plotted on the graphs for direct comparison with water levels. The hydrographs are updated and reviewed weekly. An example computer-generated hydrograph is shown in Fig. 1.

The major problem in using wells to detect changes that might be premonitory to earthquakes is filtering out water-level changes due to other causes. Each well record has its own peculiarities because of different well construction, aquifer characteristics and local environment; for example, nearby wells, roads, wind exposure and drainage. The typical duration for these fluctuations varies from instantaneous to annual. In particular, we do not know the time frame of changes that might precede earthquakes; it is possible that they may be proportional to the magnitude of the earthquake. Thus, it is essential to have records not only of both short- and long-term variations in water level but also a long enough observation period to establish a normal record for each well.

The program would be far more expensive if observation wells had to be drilled. Fortunately, a large number of abandoned water wells are available for monitoring by volunteers. The wells were abandoned for a variety of reasons. Some wells were never good producers and proved to be uneconomical. In areas such as Palmdale, publicly owned water districts were formed, providing users with water lines and permitting privately owned domestic wells to be abandoned. In other areas, agricultural projects have been abandoned along with the wells drilled for irrigation. Enthusiastic cooperation has been obtained from the owners of these wells.

In general, the wells range in depth from 20 to 100 meters, although a few reach several hundred meters in depth. Water levels commonly occur from 10 to 40 m. The observation wells, which were selected from a canvass of nearly 200 wells, penetrate a variety of rock types along and within the fault zones, including basement complex, volcanic rocks, ancient lake sediments, alluvial valley fill and fault gouge. The distribution of wells permits comparison of water-level changes in different rocks within and outside the fault zones. Diurnal fluctuations in atmospheric pressure are the principal cause of short-term variations seen on the Stevens recorder charts. Long-term changes can be seen on the hydrographs of the weekly observations. Levels in most of the wells rose as a result of the winter rainstorms; other wells have been relatively unaffected. By study of the response to rainfall and barometric pressure, wells which may be sensitive strain meters have been identified.

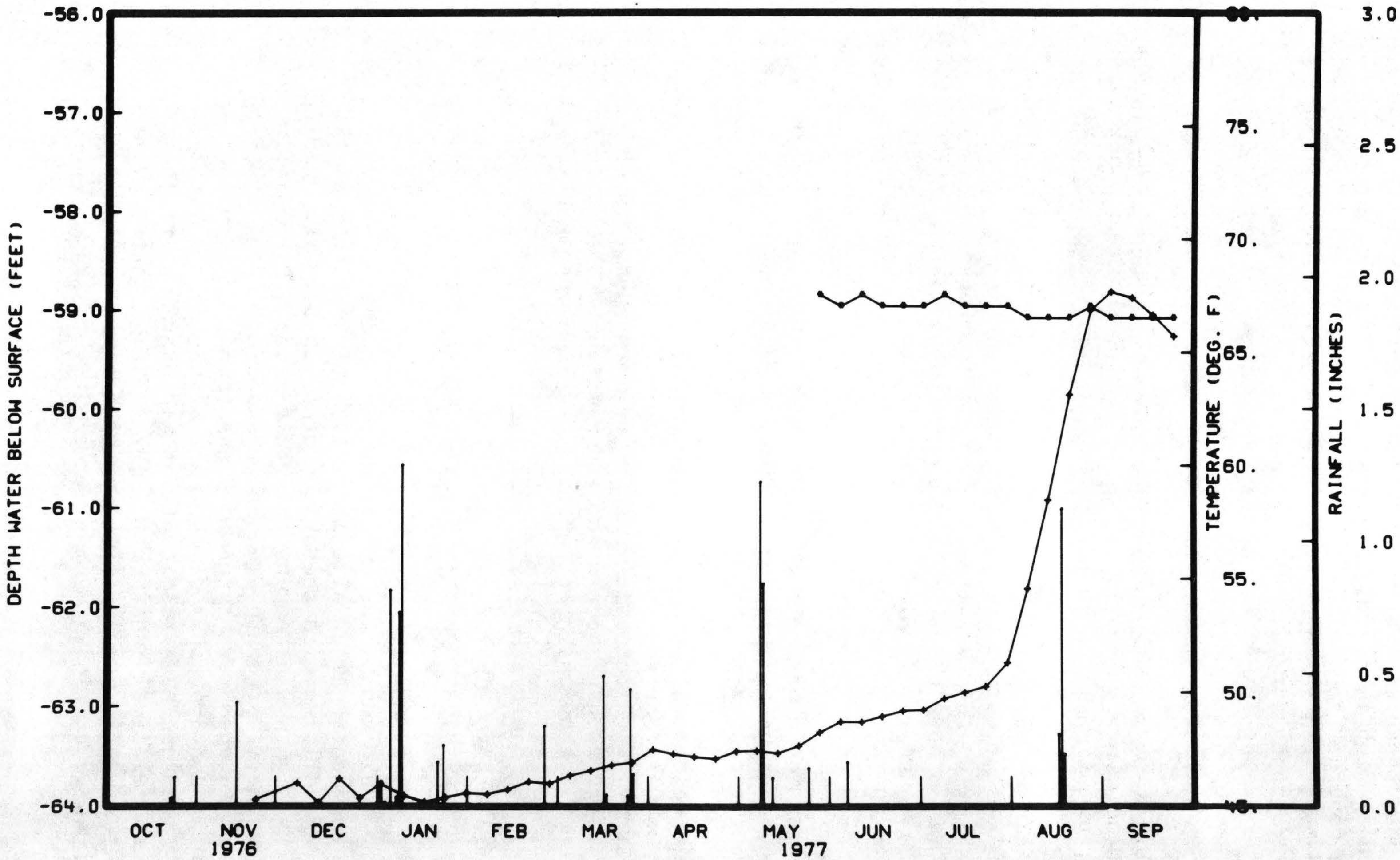

Figure 1 - Weekly observations of water level (+) and temperature (*) in well number 05N/12W-03N01 and rainfall (·) during 1976-1977, Palmdale area

Seismic events associated with the segments of the San Andreas and San Jacinto fault zones being monitored have not exceeded M 3.3. The nearest epicenter (M 3.0) to an observation well was about five miles away. No abnormal water-level or temperature changes premonitory to the earthquakes have been identified. This result is not unexpected because of the small magnitude of the earthquakes and their distance from our observation wells.

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Ground-Water Monitoring and Analysis as an Aid in Earthquake Prediction

CA 77-333

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Investigations

1. Evaluated the effects of temporal and spatial changes in water level and temperature in selected wells, using records from continuous water-level, temperature, and microbarograph recorders, in the area of the Southern California Uplift to determine if these changes may reflect strain changes and therefore act as precursors to earthquakes.

2. Expanded the original 1977 network of instrumented wells, most of which were in the vicinity of Palmdale. This expansion was done to include wells more sensitive to earth tides in geographic areas having higher seismic activity than the central Palmdale area. Eight wells are presently being monitored (fig. 1) with continuous analog water-level recorders. The wells are at Twentynine Palms near the Surprise Spring fault; Copper Mountain near the junction of the Copper Mountain and Pinto Mountain faults; Imperial near the Imperial fault; Koehn Lake in the Garlock fault zone; Newhall near the San Gabriel fault; and at Leona Valley, Palmdale, and Littlerock in the San Andreas fault zone. The well at Leona Valley has a recorder continuously monitoring the water temperature at the bottom of the well, 155 feet below land surface.

3. Expanded the original 1977 network to include four continuous-recording microbarographs to assess atmospheric-pressure influences and correct the water-level data for atmospheric effects.

4. Continued collection of air temperature, rainfall, and pumpage data at Palmdale and Twentynine Palms to aid in data reduction.

5. Began analysis of water-level response to earth tides, with special emphasis on periods preceding earthquakes.

Results

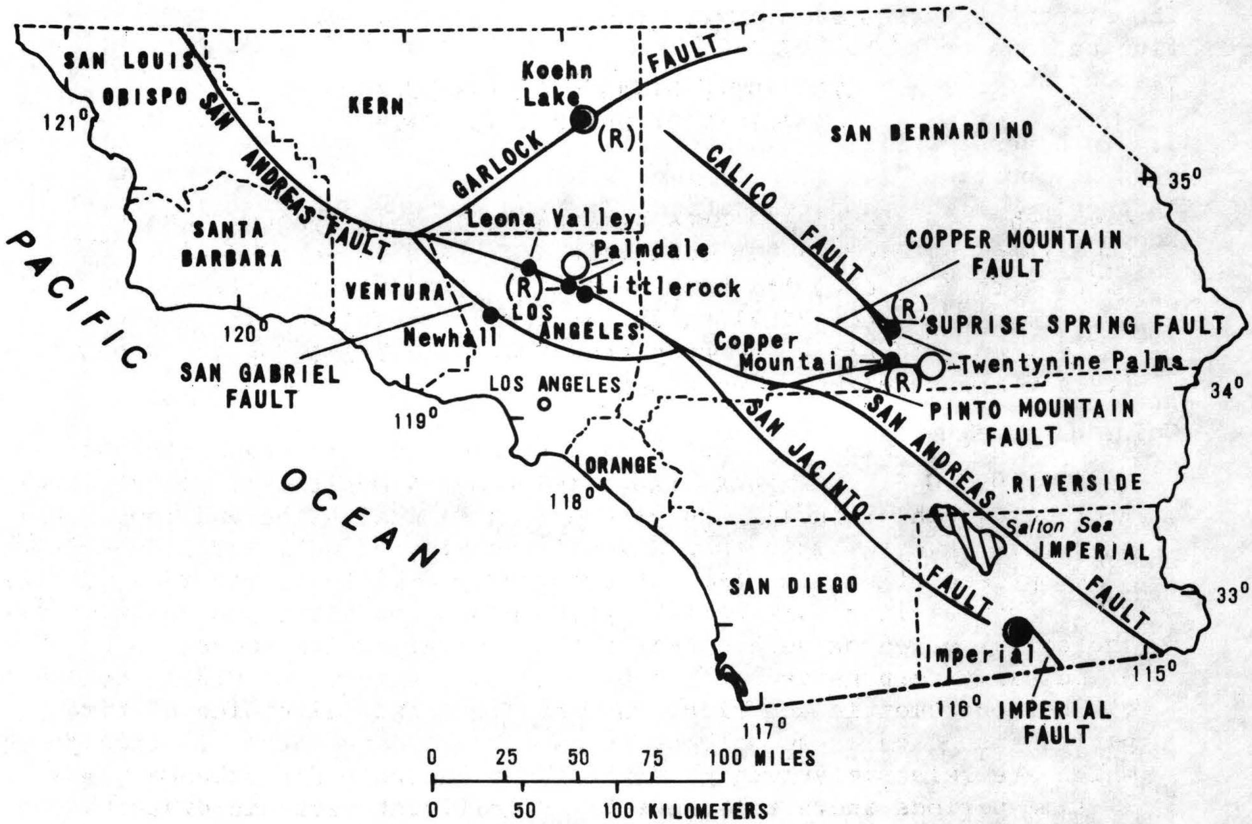
1. A comprehensive network of water-level, temperature, and atmospheric pressure recorders has been established in southern California and is in full operation. This network, consisting of eight wells equipped with analog water-level recorders, one temperature probe and recorder, and four microbarograph recorders, is strategically placed near major faults (fig. 1) and is providing a data foundation upon which to base future work.

2. An analysis of the water-level recorder charts has shown that all water levels seem to respond normally (inversely) to barometric pressure changes; however, it appears that water-level responses to earth tides in some wells are normal (direct), whereas in others they are reversed (fig. 1). Normal water-level fluctuations are upward in response to increased gravitational attraction of the sun and moon. Reversed water-level fluctuations are downward during increased gravitational attraction. The effect of earth tides on water levels in wells that have reversed fluctuations seems to be much larger than that on wells having normal responses.

3. In several wells the water-level changes in response to earth tides show an apparent "lag effect" during the period preceding some known earthquakes. This apparent effect, however, is not observed for other known earthquakes. The "lag effect" appears to consist of a gradual shift in time of the maximum and minimum peaks on the water-level recorder chart, such that shortly preceding the earthquake these peaks may be 180° out of phase with what would be expected, as the result of earth tide influences (adjusted sea tide tables are used). Comprehensive analysis is necessary to determine the significance of this anomaly. Coinciding with this observation, in some instances, are changes in rate of long-term water-level rise or decline.

4. All data obtained have been microfilmed, and copies of the microfilm and paper prints were furnished to the Branch of Earthquake Mechanics and Prediction in Menlo Park, Calif., and also to Dr. Philip Westlake (consultant) of Environmental Dynamics, Inc., for computer tabulation and analysis.

5. A preliminary draft of a report, "Ground-Water-Level Monitoring in Earthquake Prediction," by W. R. Moyle, Jr., has been prepared and is presently in review. The report presents selected data collected for this project, with some preliminary analysis.



EXPLANATION

● WELL WITH WATER-LEVEL RECORDER

(R) Indicates well showing reversed water-level response to earth tides

○ MICROBAROGRAPH RECORDER

FIGURE 1.--Map of southern California, showing location of selected faults and water-level and microbarograph recorders.

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SUMMARY OF SEMI-ANNUAL TECHNICAL REPORT

STOCHASTIC SIGNAL PROCESSING AND ANALYSIS OF WATER LEVEL DATA

Research into stochastic data processing of well hydrographs and associated parameters has been initiated, and is on schedule. EDI's major effort to date has been devoted to two areas: determining the project's theoretical needs for system identification and setting up software to process the data. The following are specific items which have been emphasized.

1. The following data has been received from two organizations, namely, U.S.G.S. of Laguna Niguel and Lamar & Merifield: water level, microbarograph, rainfall, temperature, and tidal highs and lows. All told this involves more than a year's backlog of well level data which is comprised of both continuous and weekly well level records. Certain wells for specific time periods were chosen for pilot processing. The choice was based on an assessment that certain wells appear to be principally responsive to: a) barometric changes, b) tidal changes or c) both barometric and tidal changes. The initial choice of time periods is based on an attempt to categorize data into: 1) time periods which are relatively free of significant tectonic disturbances, and 2) time periods where some possibly significant tectonic disturbances occurred.

2. Pertinent software and related documentation has been collected. This encompasses computer programs for tides, energy and power spectral density, regression, Kalman filtering, system identification and other computer programs which are being included in the software operating system. In addition, available statistical packages are being surveyed for their applicability and cost effectiveness.

3. Software to digitize the data has been completed. A Tektronix 4081 Minicomputer with an associated tablet for the digitizer input is being used. The data stored on the system floppy disk is then transferred via the U.C.L.A. campus computing network into the IBM 360, where it is converted into APL files. EDI has been investigating various aspects of the digitization requirements such as: a) optimal methods for digitizing data recorded on microfilm, b) advantages of enlarging

pen recorder data prior to digitization, c) how to process blurred data (when for example, the only microbarogarph data in the area for a given time period is blurred), d) the necessity for least squares calibration of water level data, e) the provision for adjusting the starting time of the sampling interval for best time alignment of the barometric and water level data.

4. Procedures have been developed to compute energy spectral density effectively and catenate records incorporating appropriate windows. This includes the use of the Fast Fourier Transform for the estimation of energy spectral density based on time averaging over short periodograms which have been modified by various windows.

5. Considerable investigation of tidal program requirements has been conducted. A program has been written to obtain interpolated tidal values from tidal highs and lows. Plans are being made to eventually investigate the well water level ramifications of the three-orthogonal tidal potentials plus the ocean loading. EDI has received two computer programs for the calculation of these tidal potentials from NOAA, Rockville, Md. The adaptation and inclusion of these programs in the operating system is being investigated.

6. Much of the systems software EDI developed to do the initial data processing and file handling is now in place. This includes software for processing and plotting of data in a cost effective form consistent with the needs for efficient exploratory data analysis.

7. There are few conclusions, to date, regarding the water level data since so little of it has been processed. Small amounts of water level, barometric and tidal data have been entered into the computer system and manipulated. By means of a joint computer plot close tracking of the barometric and water level fluctuations in the Lamar-Merifield well number 5N-12W-4H1 has been demonstrated. The energy spectral densities for both water level and barometric fluctuations have been calculated via the fast Fourier transform and plotted as functions of frequency. The ratio of the energy spectral densities of the water level and barometric fluctuations has been calculated and plotted as a function of frequency. Based on a simple linear model a least squares correction of water level data for baometric effects was attempted. It was demonstrated that significant reduction in the variance could be obtained and that the residuals included a strong tidal component. Due to the very limited quantity of data processed the indicated improvement has little more than limited significance. The limited quantity of data that has been processed has served mainly to exercise the software processing system that EDI has been developing.

8. The paper entitled "Kalman Filtering of Water Well Fluctuations," submitted to the American Geophysical Union May, 1978, Chapman Conference on Applications of Kalman Filter to Hydrology, Hydraulics, and Water Resources, was accepted for presentation and publication.

Since the paper presented was a revised version of the one sent to U.S.G.S. earlier, a copy of this revised paper is included in the Semi-annual Technical Report. The presentation of this paper was so well received that it resulted in an invitation for a new paper on the state of the art in this area from H. W. Shea, American Society of Civil Engineers-Chairman, Stochastic Hydraulics Task Committee on the State of the Art.

9. Various system identification methods were also explored. The data preprocessing plan with methodology for determining the structure of the input/output transfer function and its associated parameters is substantially complete. A methodology for deriving normalized water level given the input/output transfer functions was developed. Normalized water level data is water level data with the compensable variations removed With two or more inputs, such as barometric pressure and tidal potential, the input/output relationship is complex. A technique was devised to correct the water level data for multiple inputs, and at the same time take into account the initial conditions.

10. The most recent extensive rainfall in Southern California has caused concern that the data of the last few months will be unduly "corrupted" unless additional data processing measures are introduced. Because this is a complication that was not anticipated, an appropriate rainfall runoff and infiltration model may have to be developed in order to analyze certain records.

11. Plans are underway to process weekly data supplied by Lamar and Merifield, and obtain two-dimensional plots. The problem of how to process this multiple well data is being investigated. An initial approach that should be useful in experimenting with printer plotting of weekly data of many wells concurrently was developed. It is anticipated that this be done via SYMAP and/or other comparable graphics methods which would integrate all relevant data sources on a single map.

12. A previously untranslated U.S.S.R. paper entitled, "Predicting Earthquakes Hydrogeologically," by I. G. Kissin in <u>Sovetskaya Geologiya</u>, No. 3, P. 118-120, March, 1970, was translated and is included in the Semi-annual Technical Report.

Semiannual Report Summary

7 August 1978

BIOLOGICAL PREMONITORS OF EARTHQUAKES: A VALIDATION STUDY*

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Popular reports of anomalous animal behavior before earthquakes are common and extend through most of recorded human history up to the present. Birds, household pets, fish, and farm animals are cited most frequently, with occasional mention of dozens of other animals with which man comes into contact, including those in zoos.

Unfortunately, these reports are of little scientific value because they are anecdotal and subject to the inaccuracies of observations, recall, and assessment of significance that usually accompany laymen's reports of disasters. Moreover, the reports provide scanty data and the credentials of the observer are rarely provided.

The reports of unusual animal activity before earthquakes leave open the question of whether the observed behavior was abnormal or whether the activity was remembered only because it was followed by an earthquake. Without a data base of normal activity with which to compare them, these observations are merely suggestive.

No concerted effort has been made in the United States to gather animal behavior data either before or after earthquakes. However, the recent successful short-term predictions of earthquakes in the People's Republic of China have impressed U.S. seismologists; and a principal element of the Chinese program is reports of unusual behavior of animals by volunteer observers.

The purpose of this contract is to determine whether unusual animal behavior may serve as a biological premonitor of earthquakes. To enhance the possibility of "capturing" an earthquake and for cost effectiveness, our approach incorporates some features of the Chinese program. Specifically, a network of qualified volunteer observers is being established along selected seismically active areas of California. These volunteers will collect daily observational data on the behavior of animals with which they are in daily contact by virtue of their employment or hobbies.

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*USGS Contract 14-08-0001-16784

Volunteers are being solicited through articles published in newspapers and in farm, dairy, cattle, and other organizational newsletters; by direct mail; by radio and television interviews; and by personal contact.

During the first six months of this contract, we recruited 93 volunteer observers in two of three selected seismically active areas of California. The selected areas are: Region E, in Humboldt County; Region H, primarily in San Benito County but including the eastern portion of Monterey County and the southern extremes of Santa Cruz and Santa Clara Counties; and Region F, which extends about equally into Los Angeles and Ventura Counties. Volunteers solicited thus far are from Regions E and H. Solicitation of volunteers from Region F will be pursued during the second six months of this contract.

Observers are given forms on which they rate the behavior of their animals daily on a scale of 0 to 4. Zero denotes typical behavior, 1 slightly atypical behavior, 2 clearly atypical behavior, 3 very atypical behavior, and 4 behavior never previously observed. All scores of 2 or greater require amplification on the back of the log and reporting via the hot line (described below). Each log sheet can accommodate 28 days of observations. When completed, each log sheet is mailed to SRI for analysis. Any observations scored 2 or more that have not also been reported on the hot line are not considered reliable for data analysis.

The toll-free (WATS) hot line at SRI is operational 24 hours a day, 7 days a week. Volunteer observers are instructed to call the hot line on a designated day once weekly to check in as well as to use it any time they observe an instance of unusual animal behavior. No specific instructions are given about what type of behavior is considered unusual; animals differ considerably in their "normal" behavior, so the observers are the judges of unusual behavior.

The hot line system incorporates a Model 696 Remote Ansaphone unit (Dictaphone Corp.) and a Call Diverter.* The Ansaphone unit accepts calls with a 13-second preprogrammed recording requesting the caller's name, code identification, location, the time, date, and message. The caller's message is recorded on tape. As soon as the caller hangs up, the call diverter unit automatically dials the Pacific Telephone Company's time circuit (POPCORN) for the exact time, which is also recorded on the tape. The system is voice actuated, and 20 seconds is allowed for recording the time. The date and time (including AM or PM) are telephone into the hot line twice daily (early morning and early evening) by an SRI staff member. Thus, the exact time of each call can be ascertained, allowing us to determine the temporal relationship between reports of unusual animal behavior and any reported seismic activity.

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*The hot line operated intermittently because of an unknown malfunction between 7 June 1978, when it was installed, and 25 July 1978, when the Call Diverter was replaced by a special circuit designed by American Communications, Inc. (San Antonio, Texas).

During the period of intermittent hot line operation, 14 observers reported 18 instances of unusual animal behavior, most of which were rated 2 on the log sheets. Of the 18 reports, 13 were unacceptable because they referred to behavior that occurred from hours to several days before the hot line report. Of the remaining 5 reports, 3 were of felt earthquakes and the other 2 were of unusual animal behavior that were reported on the hot line as soon as observed. To change this pattern of observing, we will endeavor (in our monthly newsletters as well as by direct mail or telephone contact) to convince the observers of the necessity of reporting unusual animal behavior as soon as it is observed and not later.

A biologically trained field representative has been appointed in Humboldt County (Region E) to coordinate with existing observers and to solicit new ones, especially in remote regions on or near active fault zones. A field observer will also be appointed in Region F. Region H will be monitored by project staff from Menlo Park.

To keep observers motivated, we issue a monthly newsletter, call them after they have been in the program from 2 to 4 weeks, have the field representative contact them, and provide subscription to the USGS Earthquake Information Bulletin.*

Dr. Verosub, UC Davis, has agreed not to interview any of the observers in our program, should an earthquake occur in their locale. (The Davis group is under contract with USGS to intensively interview residents near the epicenter after an earthquake has occurred.)

During the balance of the contract year we will concentrate on soliciting observers in Region F (Southern California) and expanding the existing network, especially along the fault zones.

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*Arrangements have been made with Dr. Henry Spall, editor, to send the USGS Earthquake Information Bulletin free of charge to all volunteer observers, starting at the end of their second month of active participation.

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Final Report Summary

Institute of Geophysics and Planetary Physics
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October 27, 1978

Can Animals Predict Earthquaks? A Search for Correlation between Changes in the Activity Patterns of Two Fossorial Rodents and Subsequent Seismic Events

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Reports of unusual animal behavior prior to earthquakes have recently attained a level of notoriety among both scientists and laymen in the United States. The widespread interest is largely the result of the spectacular and widely publicized success of the Chinese in predicting the devastating Haicheng earthquake of 4 February 1975. Reports of unusual animal behavior appear to have figured prominently in the prediction process, although their importance relative to observations of physical precursors is not entirely clear. The Haicheng earthquake is apparently not an isolated example. Allen et al. (1975), reporting on the first visit of an American seismological delegation to China, state, "In three carefully documented examples of earthquakes predicted in advance of the event, unusual behavior of animals was listed as one of the principal bases for having made the prediction.

Despite such intriguing examples, the subject remains highly controversial because virtually all of the reports are the result of casual observation rather than scientific investigation. Nevertheless, the number, diversity, and worldwide origin of the reports, together with the existence of several plausible scientific hypotheses which suggest why certain animals might behave abnormally prior to earthquakes, does not permit summary dismissal of all such reports as either fanciful, fabricated, or coincidental.

When designing an experimental study, one must bear in mind that the alleged behavioral anomalies are generally common forms of behavior, a dog barking or a horse running, for example, which simply happen to have no immediately obvious cause in the particular instance cited. In all probability most of the examples would have been quickly forgotten had not the singular event of an earthquake occurred soon thereafter. An experimental study must therefore obtain as many objective and quantitative data as are feasible concerning the behavior of the observed animals.

The present experimental study of animal behavior prior to earthquakes began in October 1976 as part of the U.S.G.S. sponsored study of the Palmdale Uplift.

Using kangaroo rats (Dipodomys merriami) and pocket mice (Perognathus longimembris) as experimental subjects, we are continuously instrumentally monitoring the activity of the animals to determine whether correlations exist between changes in the pattern and intensity of their activity and subsequent seismic events. Part of the animals are housed out of doors in artificial burrow systems exposed to the natural environment. The remainder are housed in cages containing running wheels in an indoor facility which controls the light and temperature within the cages. The animals are located in the Big Morongo Wildlife Reserve adjacent to the town of Morongo Valley, San Bernardino County, California. The reserve is located within a seismically active region near the zone of maximum uplift of the most recently defined Palmdale Uplift (Bennett 1977) and within a few kilometers of the active Banning-Mission Creek branch of the San Andreas Fault.

The behavior we are monitoring is gross motor activity as manifested by the use of a running wheel or passage of an animal through a switch gate. Located in an air conditioned room on the reserve is an array of 20 isolated running wheel cages, each housing a single kangaroo rat (Dipodomys merriami). Each revolution of the wheel closes a microswitch and the event is recorded on magnetic tape via a single channel of an event recorder. Most animals are maintained on an artificial light cycle consisting of 12 hours of bright light and 12 hours of very dim light which is either in phase or 180° out of phase with the local natural light cycle.

A second monitoring facility is located out of doors in an open field. We are currently monitoring both kangaroo rats (D.merriami) and related, but smaller, pocket mice (Perognathus longimembris). Each animal is housed individually in an artificial burrow system which is intended to simulate a natural burrow. Each burrow system contains three activity boxes. One box is at ground level and exposed to the natural light cycle; one is buried just below the surface, and one is buried at a depth of about 30 in. The boxes are connected by PVC pipe so that each animal has free choice of the box it occupies. Each box is divided into three sections and contains three activity gates triggered by the passage of an animal. The animal must pass through an activity gate to enter or leave a box or to pass from one section to another. One channel of an event recorder is dedicated to each box, so that we obtain a record of where and how active each animal is throughout each 24 hour day.

In its present configuration, the outdoor facility has burrow systems for 13 pocket mice and 5 kangaroo rats. The first seven pocket mouse burrow systems were installed in January 1977. In those, magnetic reed microswitches serve as the activity gate sensors. A small alnico magnet encapsulated in paraffin and surgically implanted in the abdominal cavity of each mouse triggers the switch. The passage of a mouse through the gate is then recorded via hard wire leads to the nearby event counter. To date, the survival rate of those pocket mice has equalled our original expectation. Of the seven mice originally placed in the burrows in January 1977, only one has died. Unfortunately, the burrow systems have not lived up to our original expectations, for we are no longer obtaining meaningful data from the deepest boxes. This is apparently due to the deterioration of the magnetic activity gates which resulted from excessive moisture in the soil after the heavy rains during August 1977.

In May 1978 we installed new burrow systems housing 5 kangaroo rats and 6 pocket mice. While the geometry and data production capabilities of these are practically identical to the older burrows, they incorporate several important design modifications, particularly in the electronic hardware, which will ensure superior operation. The magnetic reed switches have been replaced by LED-phototransistor activity gates. A gate is triggered when the light beam is broken by the passage of an animal through the gate. Redesign of the entire wiring configuration and switch gate redundancy at the lowest level should ensure indefinite operation despite excessive soil moisture. To date, the new systems have been operating as expected and we are confident that they will survive the anticipated winter rains.

One of our major achievements during the present contract year has been the conversion of our data recording system from Esterline-Angus pen and ink strip chart event recorders to magnetic tape cassette event counter-recorders. The new instruments can operate either as a 31 channel, 16 binary bits per channel counter, a 62 channel, 8 bits per channel counter, or any of several intermediate combinations of 8 and 16 bit channels. Because the running wheel systems yield from one to two orders of magnitude more counts per unit time than do the burrow systems, we were operating the indoor recording system as a 16 bit per channel counter which records the number of wheel revolutions occurring during a 10 minute interval and the outdoor system as an 8 bit per channel counter which records the number of switch gate activations during a 20 minute interval. At these counting intervals,a tape cassette lasts about 23 days (46 days) for the indoor (outdoor) facility, although to allow a safety margin and to keep abreast of the data we retrieve the tape every 21 days (28 days). The new recording system is far superior to the old since the data are now both quantitative and immediately available for computer processing. Development of the software for data storage and first order (or 'quick look') processing and display was completed during the final quarter of the contract period. We can now obtain a computer printout which displays each animal's activity pattern in a form similar to that previously obtained from the pen and ink recorders. However, the number of counts accumulated during each 10 or 20 minute interval now appear in place of the earlier pen stroke. From the numerical data we compute various quantities for each days record for each animal. These numbers characterize the duration, distribution and intensity of activity for each day, and they are scanned for variation which exceed the normal day to day variation.

During the past year only one earthquake was felt at the site (8:03 PM PST, 28 April 1978, M=4.2). The epicenter was located about 8.5 km due north of the site. Only the indoor running wheel facility was producing numerical data at that time. The data for a 22 day period including the day of the event have been processed, but we have not yet critically assessed the results. A number of behavioral anomalies were recorded for several animals during the days immediately preceding the earthquake. At present we are not prepared to say whether any or all of the anomalies noted were related to the upcoming earthquake or were simply coincidental. We are certainly not aware of any environmental event not related to the earthquake which would account for the observed anomalies. However, not all animals exhibited such anomalies, and anomalies which occurred at scattered times during the 22 day record or many days prior to the earthquake also occurred. For the moment we shall be content to state that our quick look analysis does not appear to favor an entirely negative result.

PROCESSING OF MICROEARTHQUAKE DATA
FOR EARTHQUAKE PREDICTION

14-08-0001-16761

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GOALS

Develop computer programs which would aid seismologists in preparing a complete, accurate, and objective database for earthquake prediction research.

INVESTIGATIONS

One week of seismic data from the Caltech Earthquake Detection and Recording (CEDAR) system which monitors the joint USGS-Caltech seismic network in Southern California was studied. This database consisted of over 2500 seismograms, nearly 1300 hand picked P wave arrivals, and nearly 600 hand picked S wave arrivals from 63 seismic events. The hand picked P wave arrivals were used both to understand how well seismologists picked arrivals and to compare with computer picked arrival times.

RESULTS

1 Rather than develop a better single channel picker, it was decided to feed information from other sensors back into the single station picking algorithm. This was done by comgining the processes of picking arrivals and locating the event. First, arrival times are determined by applying a picking algorithm (Anderson, 1978) to each seismogram. The arrivals are then used to determine an initial location for the event. Arrivals which were missed or were inconsistent with this location are repicked using more appropriate

parameter settings. The earthquake is then relocated. This process may be repeated until a stable set of arrivals is determined. To make the location procedure resistant to arrival time errors a three step location algorithm is used. Before a location is determined, most large errors are removed by a pairwise consistency check. The order in which the arrivals occur across the network is then used to determine a starting epicenter, and the hypocenter is determined by a nonlinear robust regression.

2 An investigation of a number of robust earthquake location methods were carried out. In a machine environment, a location procedure must be robust since errors are quite likely (at least initially). However, this work clearly demonstrates that even with hand picked data, a robust location method should be used. This is particularly true if P and S wave arrival times are used in the location. Buland (1976) has shown that using both P and S arrivals stabilizes the location process and provides much better depths than using only P arrivals. However, S arrivals are much harder to time accurately than P arrivals since they occur in the P coda and are likely to be contaminated by scattered energy. Thus a robust method is definitely required.

3 A comparison between a robust location method and the least squares method shows that the robust method provides better locations. However, the performance of the robust method can be effected by a poor choice of initial location. Normally the first station to report an arrival is used as the initial location. However, the earliest station is typically 11 km. and as much as 90 km. from the epicenter. A new method which uses the order in which arrivals occur at different stations has been developed to provide a better initial location. Since only the arrival order is used and not the actual arrival times, grossly inconsistent arrivals will not affect the location. Another advantage of the method is that it does not depend on a crustal velocity model. The arrival order location is usually within 3 km. and was never more than 14 km. from the final epicenter and provides a better initial location than the first station for 95 percent of the events studied.

REFERENCES

Anderson, K.R., Automatic analysis of microearthquake network data, Geoexploration, 16, 159-175, 1978.

Buland, Ray, The mechanics of locating earthquakes, Bull. Seis. Soc. Amer., 66, 173-187, 1976.

Summary of Technical Report No. 1 on:

Numerical Methods in Seismology: Ray-Tracing and Inverse Problems

Herbert B. Keller

Applied Mathematics, CalTech

August 1, 1978

Fast, efficient and accurate computer codes are under development for computing the rays joining two specified points in an inhomogeneous medium containing discontinuity surfaces. The methods employ a very sophisticated two-point boundary value problem code with automatic net selection and variable order of accuracy. Testing on a variety of inhomogeneous models has begun. Applications to the inversion of arrival time data are also under study. Even more efficient codes are being developed and tested for heterogeneous models.

Semi Annual Report Summary Update
Establishment of a Southern California Geophysical Data and Analysis Center
U. S. Geological Survey Contract No. 14-08-0001-16629

Robert F. Nickerson
Carl E. Johnson

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SUMMARY - Project CROSS

During this 4 month period, all TIM units originally ordered (19) have been delivered by the vendor (Digital Engineering Company). Currently there have been three units deployed as requested by 2 of the Principal Investigators. They are as follows:

Location	Principal Investigator
Kresge Laboratory - Pasadena	Data Center Reference installation
Palmdale Telephone Office - Palmdale	Theodore Madden
Buck Canyon - Yjunga	Bruce Clark

These units are returning data in a daily routine manner.

In addition we placed a trial installation at the Goldstone Tracking Station for a period of several weeks. During this time data was collected from a gravimeter and telemetered to the Data Center every 24 hours. Figure 1 shows a plot of the data.

SUMMARY - Project CEDAR

During the last reporting period the implementation of the CEDAR system was completed so that all of the processing, from analog signal digitization through final catalog preparation, is fully automated and in routine production. Our accomplishments during the last fiscal year include:

> The development of a magnitude scale, M_{CA}, that permits the assignment of magnitude from any "on scale" portion of the post S coda.

The incorporation of this technique together with automatic determination of local magnitude, M_L, from amplitude data entered at the time final locations are computed.

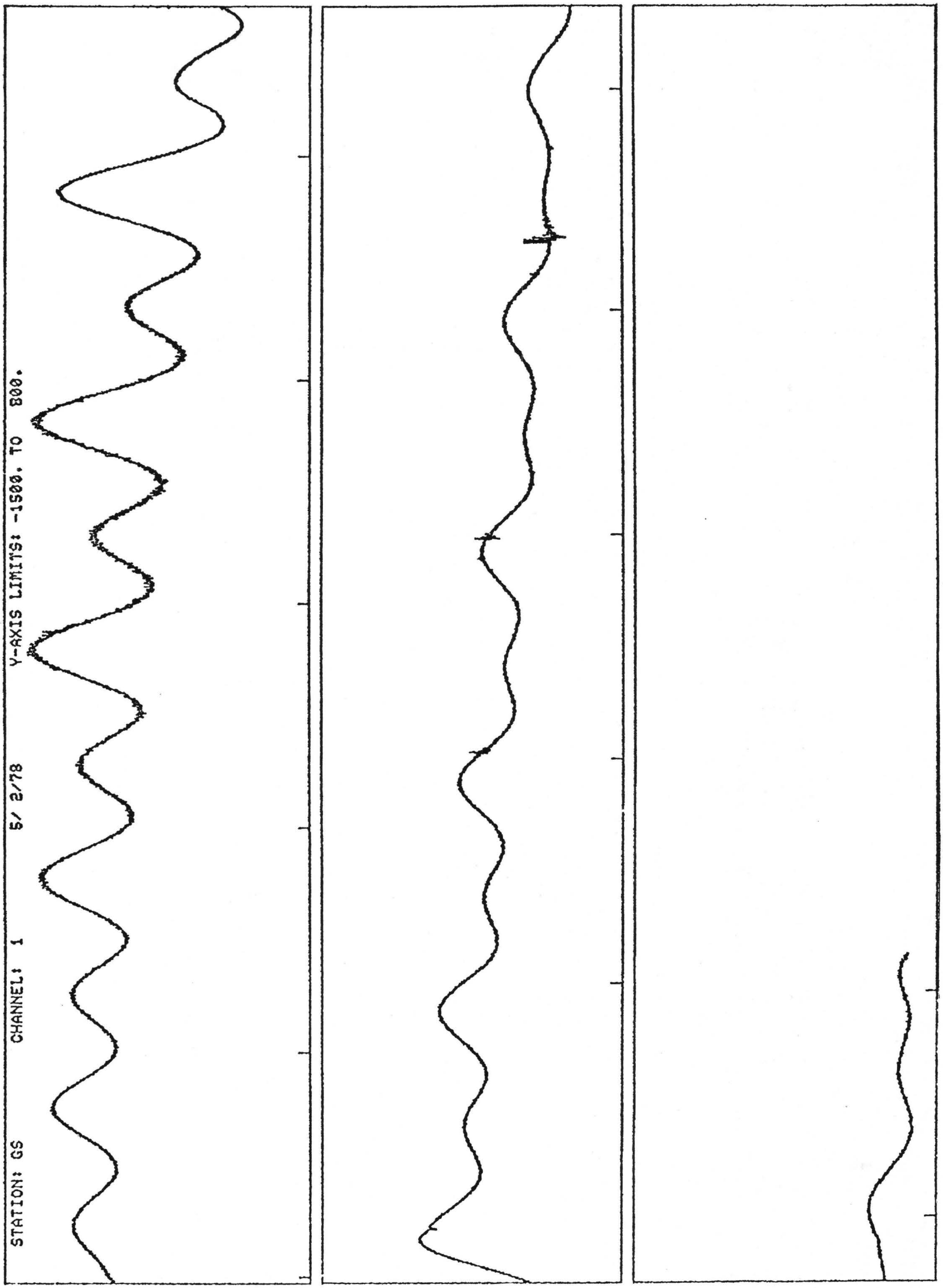
A programming system was developed and tested that allows the conversion of CEDAR digital data tapes into an external data exchange format that should be easily useable by persons wishing to conduct research with CEDAR system event data.

A system of programs was developed and tested that allows an a priori assessment of the magnitude detection threshold at any point in southern California. This program is currently in use for the purposes of adjusting network detection parameters to obtain uniform coverage, identify irremidiable holes in current station distribution, and to assess the relative worth of particular stations of the network.

The design and implementation of a comprehensive editing and data manipulation package for preparation of final locations and catalog preparation. This package includes a master event capability which was used to provide an accurate analysis of the Santa Barbara Earthquake (M_L = 5.1) within 48 hours of its occurrence.

An extraction and graphics package including stereoscopic projections from any viewpoint and seismicity mapping capability allowing for most common map projections, faults and cultural details, and variable character, character SHE, and color options.

Some of the above accomplishments were supported under other grants and contracts but are included here because of their relevance to the support and operation of the Southern California Data Center.


STATION: GS
CHANNEL: 1
5/ 2/78
Y-AXIS LIMITS: -1500. TO 800.

LATE HOLOCENE BEHAVIOR OF THE SAN ANDREAS FAULT

U.S.G.S. Contract No. 14-08-0001-16774

Kerry Sieh, Calif. Inst. Technology

Pasadena, CA 91125 (213) 795-6811 X2115 or 2456

This year's contract is supporting continued investigations of the behavior of the San Andreas fault during the past few thousand years. The purpose of these studies, now in their third year, is to gain an understanding of the long-term slip rates along the fault and the frequency and spatial relationships of large earthquakes along the fault. The five papers listed below describe previous work on 1) fault slip associated with the great 1857 earthquake; 2) prehistoric large earthquakes caused by slip on the San Andreas near Palmdale and in the Carrizo Plain; 3) an average slip rate along the fault for the past 3400 years; 4) the felt effects of the 1857 earthquake; and 5) foreshocks of the 1857 event which pin down the main shock epicenter and direction of rupture.

Recently, I have begun geomorphic studies aimed at determining the amount of fault slip associated with the latest large (pre-historic) event(s) on the San Jacinto fault near San Bernardino and on the San Andreas fault between San Bernardino and the Salton Sea. With Dick Jahns I am continuing to study the past few prehistoric events and the related late Quaternary geology of the San Andreas fault in the Carrizo Plain.

Also, I have begun subsurface studies of the San Andreas fault adjacent to the Salton Sea and the San Jacinto fault in San Bernardino Valley that may yield information on the timing and size of recent pre-historic slip events on these two faults.

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Sieh, K.E., 1977, A Study of Holocene Displacement History along the South-central Reach of the San Andreas Fault: Ph.D. dissertation, Stanford Univ., Standford, Calif., 219 pp.

Sieh, K.E., 1978a, Central California foreshocks of the great 1857 earthquake: Seismol. Soc. America Bull., 68, no. 6.

Sieh, K.E., 1978b, Pre-historic large earthquakes produced by slip on the San Andreas fault at Pallett Creek, California: Jour. Geophys. Res., 83.

Sieh, K.E., 1978c, Slip along the San Andreas fault associated with the great 1857 earthquake: Seismol. Soc. America Bull., 68, no. 5.

Reduction of Noise in Precursor Measurements

8-9960-02111

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The objective of the project is to develop procedures for reduction of the noise in measurements of earthquake precursors caused by sources that are not earthquake related. Removal of these extraneous effects will help produce accurate uncontaminated observations of tectonic phenomena that are important to the development of a scientific understanding of the physical processes that precede earthquakes. Reduction of noise will also aid in the development and application of procedures for classifying a data set as premonitory or not premonitory to an earthquake.

Currently an effort is underway to develop techniques to remove from the data of tectonomagnetic experiments the geomagnetic variations not caused by changes in crustal stress. This investigation utilizes concepts of statistics, signal processing, and time series analysis.

Consideration of the known mechanisms that may possibly cause variations in differential geomagnetic field measurements suggests that the relations among the data at the different sites are generally linear, and hence multivariate linear methods may be appropriate for noise reduction. For the variations caused by conductivity anomalies, the relations are linear; but because of the nature of electromagnetic induction and current distribution they are frequency dependent and noninstantaneous, in general, although these effects may not be significant at periods longer than several days. Careful attention should therefore be given to the choice of a frequency range of interest and to the use of appropriate frequency selective filtering.

Linear regression of magnetic field values from one site against those from several other sites can be used to reduce noise in tectonomagnetic observations at periods greater than a day. No other linear instantaneous procedure using the same data can achieve a smaller RMS residual, although such a procedure might yield a better signal to noise ratio if some sites have tectonomagnetic signals of significant energy. For total field data from central California, the linear regression method provides a reduction in the noise level, compared with two-site differences, of roughly a factor of two on the average. The effectiveness of the method varies considerably from site to site. The sensitivity of the method to missing data can be reduced somewhat by using subset regressions. It is possible to find regression expressions that remove most of the long-period variations (longer than about 100 days) from the available data, although they may not be statistically reliable. Apparently the long-period variations either are not highly correlated among the sites or have different relationships between the sites than do the short-period variations.

Theoretical Mechanics of Earthquake Precursors

8-9960-02115

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Investigations

Formulated strain softening mechanical models for earthquake instability and precursors.

Results

Numerical and analytic models for earthquake instability due to strain softening on two- and three-dimensional vertical strike-slip faults and two-dimensional thrust faults have been formulated and analyzed. Simulations show that for all geometries, both unstable deformation modes (earthquake analogs) and stable modes (rapid, aseismic fault slip episodes) are possible according to the stiffnesses of the fault and elastic surroundings. Accelerating fault slip near the inferred earthquake focus always occurs and causes accelerating deformation rates at the free surface near the inferred epicenter. Computed uplift fields for the thrust model agree reasonably well with uplift observed before the 1971, M=6.4, San Fernando earthquake. With the models, one might be able to invert sufficiently precise geodetic data to determine the likelihood of instability in the field.

Reports

Stuart, W. D., and Archuleta, R. J., 1978, Strain-softening models for earthquake precursors and instabilities (abs.): XII Symp. Math. Geophys., Caracas.

Archuleta, R. J., and Stuart, W. D., 1978, Dynamic rupture following instability of strain softening earthquake models (abs.): XII Symp. Math. Geophys., Caracas.

Stuart, W. D., Strain softening instability model for the San Fernando earthquake (abs.): 1978 Fall AGU Meeting.

Archuleta, R. J., and Stuart, W. D., 1978, Instability model for three-dimensional strike-slip earthquakes (abs.): 1978 Fall AGU Meeting.

Jones, T., and Stuart, W. D., 1978, Strain softening fault laws leading to earthquake instability: 1978 Fall AGU Meeting.

Stuart, W. D., 1978, Strain softening instability model for the San Fernando earthquake: Science, in press.

Stuart, W. D., and Mavko, G. M., 1979, Earthquake instability on a strike-slip fault, Jour. Geophys. Res., 84, in press.

STUDY OF RESERVOIR INDUCED SEISMICITY

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SUMMARY

A study of reservoir induced seismicity has been undertaken to evaluate the geologic, seismologic, and hydrologic factors significant to reservoir induced seismicity, develop a more reliable method for evaluating the potential for reservoir induced seismicity, and evaluate the theoretical bases of reservoir induced seismicity. To date, data gathering phases have identified 194 deep or very deep reservoirs (water depth greater than 92 m), 60 very large reservoirs (water volume greater than 10^{10} m^3), and 63 reported cases of reservoir induced seismicity. Ongoing data gathering efforts are continuing to accumulate data on geologic, seismologic and hydrologic characteristics for these reservoirs.

Field studies at Lake Mead have demonstrated the presence of late Cenozoic faulting; some of these faults displace Quaternary and possibly Holocene sediments.

Several seismicity catalogs have been prepared in order to assess pre-impoundment and background seismicity for areas surrounding several reservoirs having reported reservoir induced seismicity. These catalogs are also applicable to many reservoirs of interest having no reported reservoir induced seismicity.

Work during the second part of the contract period will include: completion of data compilation; site visits to at least five more reservoirs; refinement of theoretical modeling to be used in data analysis; completion and refinement of the data entry and anlaysis computer program; refinement of seismic data for selected reservoirs; and, data analysis and probabilistic assessment of interrelationships among geologic, seismologic, and hydrologic factors relevant to reservoir induced seismicity.

LAMONT-DOHERTY NETWORK OF STATIONS IN NEW YORK STATE AND ADJACENT AREAS

Yash P. Aggarwal, Principal Investigator

SEMI-ANNUAL TECHNICAL REPORT

Contract No. 14-08-0001-16750

SUMMARY

Lamont-Doherty currently operates a network of about 40 short period, single component seismic stations located in New York, New Jersey and Vermont. The ensuing data are routinely analyzed and bulletins listing earthquake locations are published on a quarterly and annual basis. The quarterly bulletin, ending 31 March 1978, is now available upon request. The annual bulletin for the year 1977 is nearing completion and should be available soon.

A number of focal mechanism solutions for earthquakes in northeastern North America were obtained using the data from the network. The solutions are either of thrust or strike slip type; no evidence is found for normal faulting.

Earthquakes in the Adirondacks and adjacent Canada predominantly show thrust faulting on north-northwest trending planes. In some cases, the shocks can be related to known geologic or topographic features.

In southeastern New York and northern New Jersey earthquake locations correlate remarkably well with mapped faults and faults inferred from aeromagnetic data. High angle reverse faulting on NNE trending planes is indicated. Focal mechanism solutions for an earthquake in Rhode Island and another in New Hampshire are almost identical to those found for earthquakes in the greater New York City area; suggesting that the principal stress directions are relatively uniform over a large area.

A paper discussing the maximum compressive stress directions and the interrelationship between seismicity, stress and geologic features in eastern North America is in preparation.

The detailed results of this research, funded by the New York State Energy Research and Development Authority and the Nuclear Regulatory Commission in addition to the U.S.G.S. should be available soon.

SOUTHERN CALIFORNIA SEISMIC ARRAYS

Contract No. 14-08-0001-16719

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This semi-annual report covers the six-month period from 1 April 1978 to 30 September 1978. It is the second semi-annual report for a three-year contract. The contract's purpose is the partial support of the seismographic arrays of the joint USGS-Caltech SCARLET (Southern California Array for Research on Local Earthquakes and Teleseisms), which is also supported by other groups, as well as by direct USGS funding through its own employees stationed at Caltech. According to the contract, the primary visible product will be a joint Caltech-USGS catalog of earthquakes in the southern California region, to be issued on a yearly basis, although quarterly maps and catalogs are also required. Figure 1 shows preliminary epicenters of events that were detected and located by SCARLET during the six-month reporting period, and quarterly maps and catalogs accompany the complete reports.

Some of the seismic highlights in the southern California region during the reporting period are these (figures in brackets indicate totals for the entire first year of the contract):

Number of located events: 3,345 [7,242, including about 900 quarry blasts]

Number of earthquakes reported to the Seismological Laboratory as having been felt: 40 [103]

Largest earthquake: M = 5.5 (5-5-78, south of Cerro Prieto, Baja California) [This was also the largest earthquake of the year. It may have been exceeded four days following the end of the period by the Bishop earthquake of 10-4-78, tentatively assigned a magnitude of 5.7]

Number of earthquakes of M = 4.0 and above: 11 [26]

Smallest earthquake reported felt: M = 2.1 (9-26-78, Beverly Hills)

Number of earthquakes for which immediate telephone information was transmitted to interested agencies, according to pre-arranged procedures: 24 [59]

It is interesting to compare the number of located events during the past year (7,242) to those of previous years: 1977: 5,042; 1976: 3,260; 1975: 2,877; 1974: 1,264; 1973: 1,414; 1972: 747. Thus, in the last six years, the number of events located has increased almost ten-fold. This is due both to the increased number of stations in the array and to the vastly improved data-analysis procedures with the CEDAR (Caltech Earthquake Detection and Recording) system.

Since the beginning of this contract, Caltech and USGS personnel have been participating on a half-and-half basis in the CEDAR timing and location routine, alternating two-hour shifts. The daily routine has taken an average of 7-8 hours, and the shared responsibility continues to be working reasonably well. Archiving, relocations, and magnitude assignments have been carried out by Caltech.

Probably the most significant seismic event during the reporting period was the M = 5.1 Santa Barbara earthquake of 8-13-78, which caused some damage in the Santa Barbara area. Figure 2 shows preliminary locations of the main shock and succeeding events through the end of the month, based on relative locations by graduate students Edward Corbett and Carl Johnson. Detailed studies of this earthquake are currently underway by several investigators, but it tentatively appears that (1) the shock occurred on a WNW-trending offshore thrust fault, with some left-lateral component of displacement, (2) the fault break was about 10 km long, and (3) the rupture was unilateral, propagating from east to west. There has been some controversy over the magnitude of the main shock, in view of the surprisingly intense ground motion, and in view of the fact that more distant stations, such as those of the Berkeley network, suggest a higher magnitude than do the nearby stations. However, 18 independent readings from Wood-Anderson-type instruments throughout SCARLET give an average magnitude of 5.1. This is supported by the coda magnitude determined by the technique of Suteau and Whitcomb.

Commencing near the end of the reporting period, Caltech is issuing a monthly catalog of preliminary epicenters, to be sent to a limited mailing list. The first mailing, in October 1978, included preliminary bulletins for the 14-month period from January 1977 through February 1978 (see below). Copies are available on request.

Only two station changes were made during the reporting period: A new 3-component station was added at Desert Hot Springs (DHS), and a new station was added to fill a conspicuous "hole" in the array at Julian (JUL). At the end of the reporting period, 149 signals were being recorded by the CEDAR system, and 142 signals continue to be recorded on De ı.

Publications

Whitcomb, J. H., Allen, C. R., Blanchard, A. C., Fisher, S. A., Guis, G. S., Hutton, L. K., Jenkins, D. J., Johnson, C. E., Reed, B. A., and Richter, K. J., 1978, Caltech-USGS monthly preliminary epicenters for January 1977 to March 1978: Pasadena, Calif. Inst. Technology, 156 p.

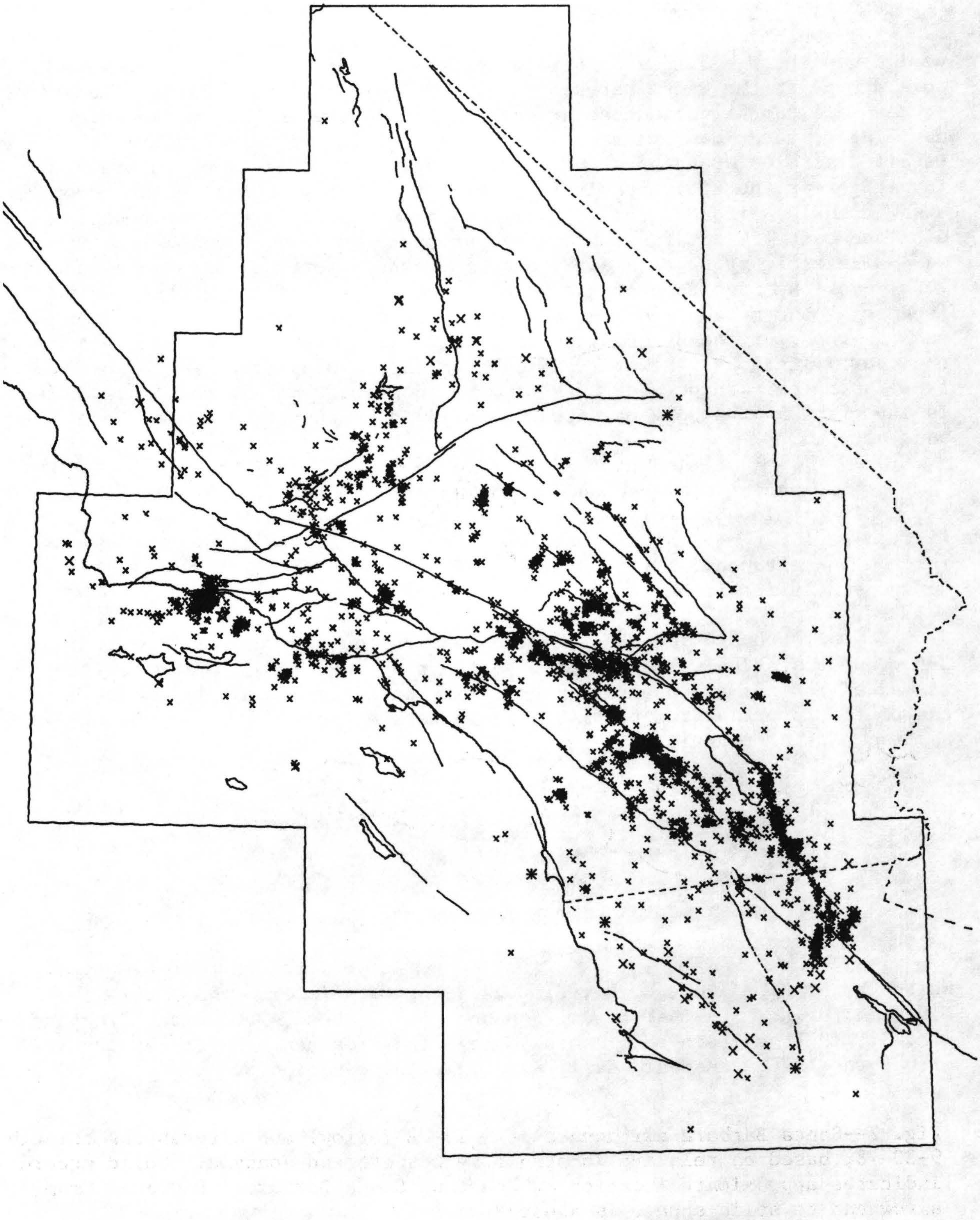

Fig. 1--Preliminary epicenters of seismic events in the southern California region, 1 April 1978 to 30 September 1978. Stars indicate events of M = 5.0 and greater; asterisks, M = 4.0-4.9; larges crosses, M = 3.0-3.9; small crosses, less than M = 3.0. Quarry blasts have not yet been removed. This maps portrays 3,345 events.

Fig. 2--Santa Barbara earthquake of 8-13-78 (arrow) and aftershocks through 9-30-78, based on relative locations by Corbett and Johnson. Solid square indicates approximate location of downtown Santa Barbara. Distance from arrowhead to solid square is about 8 km.

University of Washington

Geophysics Program

SUMMARY OF ANNUAL TECHNICAL REPORT

October 1, 1977 - September 30, 1978

Contract No.: 14-08-0001-16723

Co-Principal Investigators: R.S. Crosson, S.W. Smith

Title: Earthquake Hazard Evaluation in the Pacific Northwest

During the contract year 1977-78, operation of the western Washington seismograph network was continued in a stable configuration of 22 stations. Review of data post-1974 was completed and earthquake summaries were completed for the years 1975, 1976, and 1977. These summaries are currently being published by the State Department of Natural Resources, Division of Geology and Earth Resources. A preliminary list of 2nd quarter 1978 earthquakes is included with this report. Routine processing of records is on a current basis and it is expected that 1978 data will be available in final form early in 1979.

Other activities undertaken on this project are: a) Preliminary work on ground motion modeling was completed. A proposal was written, subsequently funded, to support this project independently. b) Analysis continues of the March 11, 1978 magnitude 4.8 earthquake in south Kitsap County. Examination of foreshock data is being made for evidence of anomalous patterns which might be of precursory nature. c) Work was continued on three-dimensional velocity modeling using a new three-dimensional travel-time analysis procedure. d) Theoretical investigation into the nature of iterative, damped least squares modeling was undertaken. Tasks (b) and (d) were emphasized in the final six months period of this project. All except (a) continue into the current budget year.

REPORT SUMMARY

OPERATION OF A SEISMIC DATA COLLECTION AND ANALYSIS CENTER IN ALASKA

Report prepared by T. Neil Davis

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November 1978

The objective of this project is to establish an ongoing program of data collection, timely data reduction and analysis of Alaskan seismic data with primary initial focus on interior Alaska. Scope of the program includes contribution to the operation of a network of approximately ten short-period seismic stations distributed along the Parks and Richardson-Glenn Highways linking Fairbanks and Anchorage. The data are being centrally recorded at Fairbanks. The scope of the project also includes data reduction and analysis with initial emphasis on regional seismicity and focal mechanisms of selected earthquake sequences.

An achievement of the past six months has been the scaling and reduction of a large fraction of data collected in interior Alaska during the epoch 1974-1977. Most of the epicenters of earthquakes occurring in that period are now incorporated into a master data file containing approximately 30,000 earthquakes representing the period 1967 to 1978.

Data currently being acquired are manually scaled from analog film records with the results being published in quarterly seismological bulletins. To date, four bulletins have been published and distributed; they cover the epochs July-September 1977, October-December 1977, January-March 1978 and April-June 1978. A fifth bulletin covering the period July-September 1978 will soon appear.

As part of a master's degree thesis program, an investigation of the aftershock sequence of the October 28, 1968, earthquake near Rampart, Alaska, has been essentially completed. Composite fault-plane solutions indicate both strike-slip and normal faulting along a highly dipping north-south zone lying parallel to Minook Creek Valley.

A determination has been made of the general levels of seismicity in the Fairbanks area and an area to the east bounded by latitudes 62° and 65° N and longitudes 141° and 146° W. The seismicity can be expressed by values for the constants a and b in the magnitude-frequency equation $\log N(M) = a - bM$, where the units are numbers of earthquakes year^{-1} degree^{-1}. Values found are, for the Fairbanks area: $a = 3.69$; $b = 0.914$; for the area to the east: $a = 2.82$, $b = 1.00$. Using these values the expected recurrence rates for earthquakes occurring within 50 miles of Fairbanks are: $M > 3.0$, 20 days; $M > 4.0$, 170 days; $M > 5.0$, 3.6 years; $M > 6.0$, 19 years; $M > 7.0$, 40 years. Earthquakes in the Fairbanks area are found to be most frequent in the immediate Fairbanks vicinity; however, the energy release during the past 70 years shows a relatively more uniform distribution.

Reanalysis of Instrumentally-Recorded U. S. Earthquakes

8-9920-01901

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Investigations

1. Relocate instrumentally-recorded U. S. earthquakes using the method of joint hypocenter determination (JHD) or the master event method, using subsidiary phases (P_g, S, L_g) in addition to first-arriving P-waves, using regional travel-time tables, and expressing the uncertainty of the computed hypocenter in terms of confidence ellipses on pairs of hypocentral coordinates.

2. Evaluate the implications of the revised epicenters on regional tectonics and seismic risk.

Results

These results cover the researches of Jim Dewey and Dave Gordon on U. S. seismicity east of 85°W and the research of Bill Gawthrop on the seismicity of the Nevada Seismic Zone.

1. First, an update on the semi-annual report covering the period October 1, 1977 to March 31, 1978: We suggested therein that earthquakes in western Virginia-West Virginia lay in on east-west zone between 80.4°W and 81.7°W at approximately 37.3°N latitude. We pointed out, however, that the west end of the zone lay in a region of coal mining and suggested that the seismicity at the west end might be triggered by mining. We have now found a catalog in which several of these events are explicitly identified as rockbursts. In our minds, this means that the other coalfield events are also probably rockbursts, and we feel that it is no longer tenable to consider the events in western Virginia-West Virginia as forming an east-west seismic zone.

2. In the eastern seaboard region, our epicenters support hypotheses that seismic activity is associated with Triassic border faults, the Fall Line zone, and faults that displace sedimentary strata beneath the coastal plain.

3. Instrumentally-recorded earthquakes occurring near Anna, Ohio since 1930 have been relocated 15-20 km NW of Anna, very near the Anna-Champaign fault.

4. In general, the differences between our epicenters and previous epicenters become more significant as we go back in time or as we consider earthquakes on the eastern Seaboard which were recorded only by stations to the North and West. In the 1970's, the NEIS began locating some eastern earthquakes using regional travel-time tables and subsidiary phases, and our epicenters are virtually identical with these. The largest difference we have yet obtained between our epicenter and a previously accepted epicenter is for the "Lake Erie" shock of March 9, 1943. The old and new epicenter differ by 75 km. The old epicenter was placed beneath the center of Lake Erie; our epicenter is in a zone of historic seismicity east of Cleveland.

5. Work has begun on relocation of earthquakes occurring since 1930 in the Nevada Seismic Zone, exclusive of the Reno-Carson City region.

Reports

Dewey, J. W., "Joint Hypocenter Determination Using Calibration Stations: Application to Eastern North America," Earthquake Notes, vol. 49, p. 35. (Paper presented at 734d Annual Meeting of Seismological Society of America, 6-8 April 1978.)

Central California Seismic Network

8-9930-01160

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Goals

1. To identify and delineate active faults in central California and to assess their potential for producing a damaging earthquake.

2. To develop improved models of the processes that generate earthquakes and of the mechanics of their sources.

3. To provide a high quality source of unreduced and reduced data on earthquakes in central California as a basis for more detailed seismic studies and for related non-seismic studies: dubbed magnetic tape library of network records of important earthquakes; earthquake phase readings and hypocenter determinations on punch-cards, computer tape, and computer mass-data storage cells; earthquake catalogs, epicenter maps, etc.

4. To develop effective seismic techniques for earthquake prediction.

Investigations

Recordings from 250 stations of the multi-purpose central California Seismic Network are telemetered continuously to the central laboratory facility in Menlo Park, where they are recorded, reduced, and analyzed to determine the origin times, magnitudes, and hypocenters of the earthquakes that occur in or near the network. Data on these events are presented in the form of lists, computer card catalogs, computer tape and mass-data files, maps, and cross-sections to summarize the seismic history of the region and to provide the basic data for further research in seismicity, earthquake hazards, and earthquake mechanics and prediction. A magnetic tape library of "dubbed", unprocessed records of the network for significant local earthquakes and teleseisms is prepared to facilitate further detailed studies of crust and upper mantle structure and physical properties and of the mechanics of earthquake sources.

In addition to its primary role in earthquake hazards and earthquake prediction studies, the network contributes to research on the sources of geothermal energy (network in The Geysers/Clear Lake region) and provides seismic monitoring for environmental hazards studies around 1) the Warm Springs Dam site northwest of Santa Rose, 2) around the Oroville and Melones Dams and Auburn Dam site in the western foothills of the Sierra Nevada mountains between Chico and Modesto, and 3) around Lassen volcano.

Results

The primary products of this project are:

1. Annual volumes for 1975, January 1979.
2. Annual volumes for 1977, August 1979.
3. Quarterly volumes for 1978, 1979, throughout 1979.

Reports

Lester, F. W., and Meagher, K. L., 1978, Catalog of earthquakes along the San Andreas fault system in central California for the year 1974: U. S. Geological Survey, Open-File Report 78-1010, 89 pp.

McHugh, C. A., and Lester, F. W., 1978, Catalog of earthquakes along the San Andreas fault system in central California for the year 1976: U.S. Geological Survey, Open-File Report 78-1051, 91 pp.

Southern California Cooperative Seismic Network

8-9930-01174

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Goals

Develop, maintain, and utilize a seismic network in southern California in close cooperation with CIT in order to develop a detailed understanding of the seismicity of southern California, and to provide an instrumental basis for the prediction of earthquakes in this region.

Investigations

1. Investigations conducted using stations of the southern California cooperative seismic network exclusive of the Imperial Valley stations are reported here for the period April 1978-October 1978. Data from these stations, currently numbering 118, are now analyzed routinely using the Caltech Earthquake Detection and Recording (CEDAR) system (refer to C. Johnson, EOS (American Geophysical Union Transactions), v. 59, p. 316).

2. We continued *in situ* timing of blasts at several quarries in southern California in order to monitor any changes in seismic velocity that might have occurred.

3. We completed experiments to modify the frequency response of the USGS telemetered seismic stations in southern California. Our objective is to reduce high-frequency noise in the seismograms recorded from these stations and to reduce aliasing in the new digital recordings by CEDAR. We concluded that a modification in the discriminator response was the simplest means to our objective and have now modified all discriminators. The modification moves the high-frequency roll-off of the discriminator from about 10 Hz to about 3 Hz, so that the overall system response now peaks in the range 1 Hz to 10 Hz. Many stations that previously produced unreadably noisy seismograms now produce beautiful seismograms.

4. We undertook an investigation of the seismicity of the eastern Transverse Ranges, including the San Bernardino Mountains (SBM), and the Little San Bernardino Mountains (LSBM). In conjunction with this study we deployed 10 tape-recorder seismic units in the LSBM for a 5 1/2 week period beginning 19 May 1978. We also timed blasts at Eagle Mountain Mine, at the eastern end of the LSBM, Cushenberry Quarry, on the north flank of the SBM, and Little Morongo Canyon, in the LSBM

(continued)

north of Desert Hot Springs. The latter blast was detonated by us (1000 lb yield). It was recorded by the 10-station seismic network in the LSBM plus 11 stations deployed in a north-south line across northern Coachella Valley.

5. We recorded aftershocks of the Bishop earthquake of October 4, 1978, using 11 smoked-drum recorders and 3 tape-recorder seismic units. The instruments were installed on October 5 and removed October 16. Other groups studying these aftershocks included the USGS from Las Vegas, Nevada, the University of Nevada at Reno, and Woodward-Clyde Consultants. A search for possible ground breakage initially proved fruitless. However, by good fortune, we made contact with an amateur geologist in the area who had discovered cracks. We have nearly completed mapping these cracks.

Results

1. The eastern Transverse Ranges, which includes the San Bernardino Mountains (SBM) and Little San Bernardino Mountains (LSBM), is an area of high seismicity in southern California. Seismicity here is of concern since these ranges border a segment of the San Andreas fault zone that has not ruptured historically. Our study is an attempt to characterize straining in this area by identifying active faults and studying focal mechanisms.

   Data since 1974 clearly show seismic lineaments, seismic "hot-spots", and aseismic areas. In the SBM, a west-trending, elliptical zone of epicenters is seen through the Kitching Peak area, between and subparallel to the Banning and Mission Creek faults. In the LSBM, west-trending lines of epicenters through Pinto Basin, Porcupine Wash, and Smoketree Wash are clearly related to mapped faults in these locations. Also, epicenter clusters appear to outline northwest-trending structures northeast of Desert Hot Springs. Prominent aseismic areas are found around the junctions of the Mill Creek and San Andreas faults and the Banning and Mission Creek faults and, also, along the Pinto Mountain fault.

   A north-trending seismicity cross-section through the SBM shows hypocenters concentrated in a V-shaped region. The bottom of the V lies beneath the Kitching Peak area at 20 km depth. A northeast-trending seismicity cross-section through the LSBM shows hypocenters concentrated in a region above and northeast of a plane that dips 40^{o}-60^{o} northeast from the Indio Hills.

   Of 11 well constrained focal mechanisms, 8 indicate strike slip on planes with average strikes of 67^{o} (left-lateral) and 337^{o} (right-lateral), and 3 indicate normal dip slip on northerly striking planes. These two types of mechanisms suggest a persistent west- to northwest-trending tension axis and interchangeable compression and intermediate-stress axis.

2. We located five aftershocks of the Bishop earthquake using readings from portable stations in order to get a feeling for the distribution of aftershocks. Three of these shocks located in an area between the north end of Wheeler Crest and Toms Place, about 30 km northwest of Bishop; one located in a area just northwest of the Tungsten Hills, about 15 km west-northwest of Bishop; and one located outside our network of portable instruments at the base of the White Mountains 20 to 25 km southeast of Bishop. Depths for the four well located shocks (Toms Place and Tungsten Hills) range from 11 to 17 km. The maximum distance among epicenters for these four shocks is about 18 km.

The search for ground breakage was initially concentrated on faults at the base of and on top of Wheeler Crest, a north-south mountain range 25 km northwest of Bishop. These faults have northerly strikes except at the north end of Wheeler Crest where strikes swing around to the west. Cracks were discovered, however, near Paradise Camp, 4 km east of the base of Wheeler Crest and also at another location several kilometers southeast of Paradise Camp. Several northwesterly (and northeasterly) striking faults are mapped through the area where the cracks were discovered. These faults offset the Bishop Tuff (age approximately 700,000 years B.P.). Scarps along these faults form the northeastern boundary of a wedge-shaped valley known as Round Valley; Wheeler Crest forms the western boundary.

The cracks near Paradise Camp are purely tensional with maximum openings of 2 to 3 mm. They are parallel to Lower Rock Creek gorge, which has a northerly to northeasterly trend. They are concentrated in linear zones that are distributed throughout a block of Bishop Tuff between the gorge wall and a mapped northwest-striking fault (with a scarp) east of the gorge. The maximum north-south extent of the area of cracking is over 1 km. The maximum east-west extent of the area of cracking, between the gorge wall and the fault scarp, is over 1/2 km. Because the cracks are purely tensional, because they are parallel to Lower Rock Creek gorge, and because they are not concentrated along a fault scarp, we conclude that they are probably not tectonic in origin but represent, rather, incipient slumping of a block into the gorge. The fact that the area of cracking is bounded partly by a fault may be important however, and we are mapping the cracks to determine if there are any subtle patterns suggestive of a tectonic origin.

Reports

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Central American Seismic Studies

8-9930-01163

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Investigations

The goal of the Central American Seismic Studies project is to search existing earthquake data for changes in seismicity patterns preceding earthquakes of magnitude 4.5 or larger. The data base for this study is the seismic data collected by networks of short-period, high-gain seismograph stations in Guatemala and Nicaragua that have been operating since early 1975.

Results

Current work is being focussed on the vicinity of two recent moderate sized earthquakes that originated on the subduction zone that dips northeastward beneath the Pacific Coast of Nicaragua. The earthquakes occurred on May 31 (M_b - 5.6) and July 20 (M_b - 5.8), 1978. These earthquakes are the largest recorded in the 3 1/2 year operation of the Nicaraguan seismograph network and subduction zone earthquakes of similar magnitude have not occurred in this region during the previous 8 years. In addition, the earthquakes are located on the opposite edges of an area on the subduction zone that is seismically quiet. The quiet area has a width of 70 km along the strike of the subduction zone and extends from a depth of 10-15 km at the Middle American Trench to a depth of 70 km near the Nicaraguan coastline. The relationship of the two recent earthquakes to the area of relative seismic inactivity is of particular interest because of the similarity to previous observed distributions of seismicity prior to mainshocks. These observations indicate that, in addition to the relative seismic quescence of the rupture zone before an earthquake, prior seismicity often occurs at the edges of the rupture zone of the main event and that the level of this prior activity increases with the approach of the mainshock. The significance of this seismically quiet area is further enhanced because it is located in a recognized seismic gap off the coast of El Salvador and western Nicaragua that is considered a good candidate for a magnitude 7 or larger earthquake. The recurrence interval for large earthquakes in this area is 50 years and this gap last broke with a series of large earthquakes between 1915 and 1926.

Despite the seismicity patterns shown by the present result from Nicaraguan seismic data and the likelyhood of an earthquake suggested by historical data, it is not yet possible to either predict or definitely state that an earthquake is pending for Western Nicaragua. Previously observed seismicity patterns prior to large earthquakes in similar tectonic settings are few and the significance of prior seismic activity is often clear only in hindsight. The 3 1/2 year recording period of the Nicaraguan seismograph network is short compared to the 50 year recurrance interval for large earthquakes. Thus, the significance of the present results is severly limited. For example, no data exists on how frequent or long lasting are the periods of seismic quiescence nor if their are periods of seismic quiescence not followed by large earthquakes.

Enhancement of Data Acquisition in the New Madrid Seismic Zone

14-08-0001-16794

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January 1, 1978 - June 30, 1978

Goals

Augment monitoring of earthquakes in New Madrid Seismic Zone by the addition of sixteen new seismograph stations.

Install three three-component digital accelerographs to obtain strong motion records for small events in the zone of major seismicity.

Investigations

The present effort involves only an augmentation of equipment. Research studies utilizing the data acquired will be performed under Contract No. 14-08-0001-16708, "Earthquake Hazard Studies in Southeast Missouri."

EARTHQUAKE PREDICTION IN PAKISTAN

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The Quetta network has been operating since June 1978. However, large gaps in the data occurred during the first 4 months of operation. The network configuration finally adopted (Figure 1) differs significantly from the design in the original proposal. Instead of 4 telemetered stations and 2 independently recording stations, we are operating 5 telemetered stations and no independently recording stations. The latter were ruled out when it became apparent that the GSP personnel could not cope with the logistic problems of having to change records every two days at a remote locality.

Some preliminary analysis of the Quetta network data has been carried out in Pakistan. The results are not yet in New York at the time of this writing so I can only approximately indicate what they are.

The highest seismic activity in the vicinity of the network during its operation this summer appears to be in two distinct areas along the Chaman fault. On 16 March 1978 an earthquake occurred near Nushki along the Chaman fault at about 29°40' north latitude. Yeats and others (1978) have investigated the intensity distribution and have concluded that the earthquake probably occurred on the Chaman fault itself. One of the two active zones along the Chaman fault appear to correspond with the epicentral area of the Nushki earthquake.

The other active area apparently also on the Chaman fault, is about 80-100 km north of Nushki. This area may correspond with the epicentral area of the 30 October 1975, magnitude 6.7 earthquake. Farah (1976) found ground fissuring and evidence of left lateral slip along the trace of the fault that occurred at the time of this earthquake. This earthquake occurred approximately at the southern end of the rupture along the Chaman fault associated with the 1892 earthquake (Figure 1).

The section of the Chaman fault between these active areas appears to be presently aseismic. The distribution of seismicity is suggestive of Mogi's (1969) donut configuration around the inactive portion of a fault preparing to rupture. The network configuration is not favorable for locating earthquakes along the Chaman fault (Figure 1). However, using master-event techniques we should obtain a fairly accurate picture of the present distribution of seismicity along this portion of the Chaman fault.

Within the network area, most of the preliminary hypocenters appear to be locate near Kolpur (Figure 1), the approximate location of the maximum intensity associated with the July 1977, magnitude 5.5 earthquake (Mirza, M.A, personal communication). These hypocenters apparently occur in the deeper part of the crust, between 25 and 30 km deep.

It has been known for a long time that subcrustal earthquakes occur in a zone north of the Makran coast and west of Quetta. Recently, Jacob and Quittmeyer (1978) have studied this seismicity and have related it to northward oceanic subduction along Makran. 400 km east of Quetta along the Indus valley the Leyah earthquake of 23 August 1955 appears also to be subcrustal with a hypocentral depth of 60 to 80 km (Quittmeyer and Jacob, 1978). One way to explain this peculiar subcrustal earthquake is that the Benioff zone associated with the subduction in Makran extends eastward to Leyah. Such a Benioff zone would also be located below Quetta. So far we have no evidence of earthquakes deeper than 30 km in the Quetta area.

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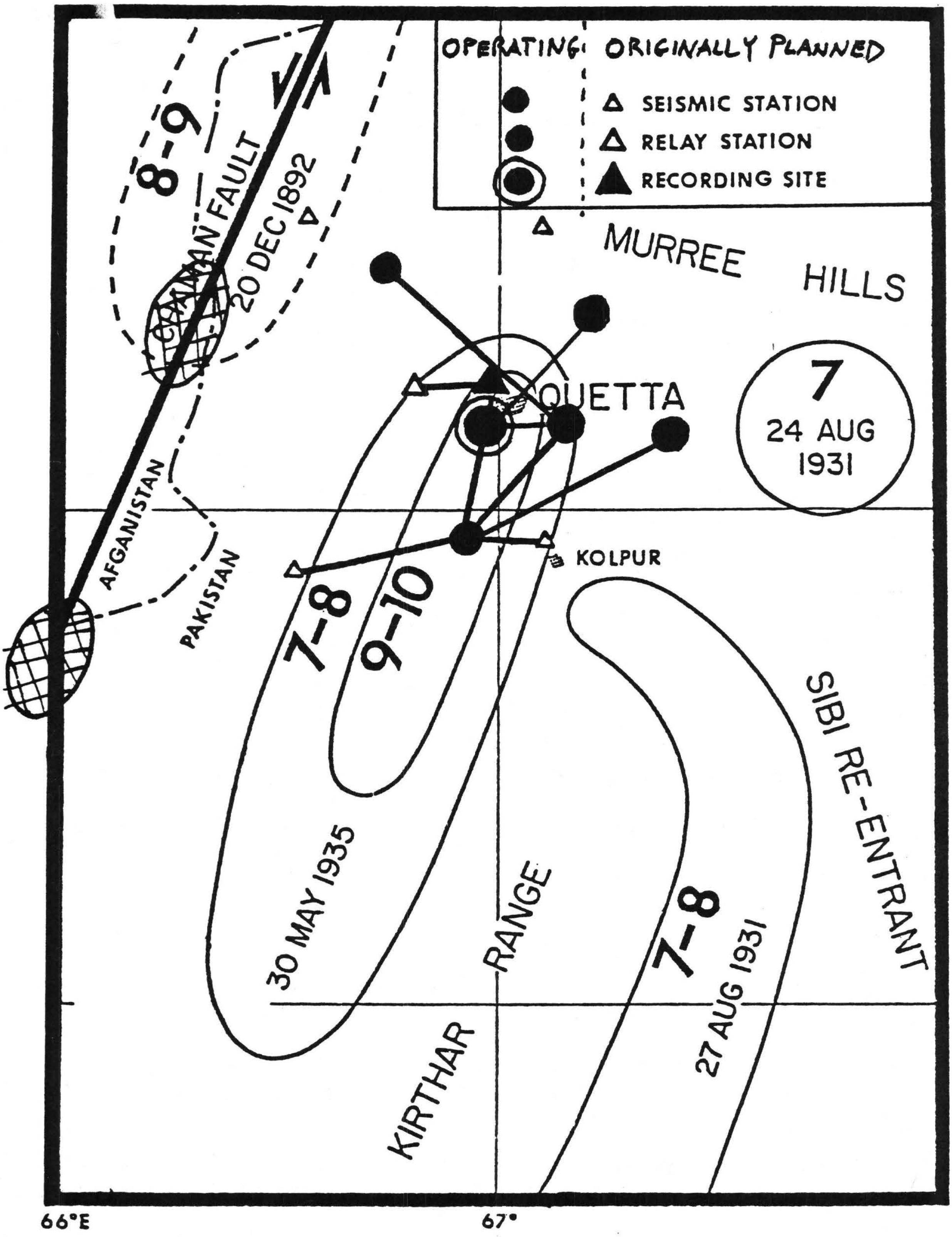

Figure 1. The presently operating Quetta Network. The change from the originally planned configuration is primarily due to absence of line-of-sight condition between the central recording station and the main relay station. The mezoseismal area of the largest earthquakes that occurred near Quetta is shown. The two intense earthquake sources along the Chaman fault detected by the network are shown by cross hatching.

Seismicity of the Rio Grande Rift

8-9920-01774

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Investigations and Results

Analysis of seismicity data through 1977 has been completed. An open file report covering results of the seismicity study has been written and is presently in the publication mill. A paper entitled "Seismicity of the Rio Grande," by Allan R. Sanford, Kenneth H. Olsen, and Lawrence H. Jaksha is being prepared for presentation at the International Symposium on Rift Zones of the Earth to be held in Santa Fe next month.

Larger regional earthquakes and explosions from 1976 to the present have been examined on the USGS and LASL seismic networks to compose a data set for a crustal and upper mantle study. A paper entitled "Estimates of relative time terms and of the P_n velocity in central New Mexico," by James N. Murdock and Lawrence H. Jaksha is being prepared for the rift conference in Santa Fe.

Large teleseisms that occurred during 1977 have been examined on the USGS and LASL seismic networks to compose a data set for a crustal and upper mantle study. A paper entitled "Teleseismic P-wave delays across the central Rio Grande rift," by William Spence and Lawrence H. Jaksha is being prepared for the Santa Fe conference.

Reports

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A FIELD STUDY OF EARTHQUAKE PREDICTION METHODS IN THE CENTRAL ALEUTIAN ISLANDS

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Summary

Attempts to restore the full Adak network to its pre-October, 1977 status have not yet succeeded, but routine monitoring continues in spite of the limited data available for event location. All events detected are logged, but only events stronger than m_b 2.5 are located by means of the data of the seven remaining stations. A successful ocean-bottom seismograph drop during July, carried out by the University of Texas, Galveston and NOAA, will provide important results for our event location capability, focal mechanism determinations and general knowledge of the local velocity structure. A large fraction of the events detected by the land-based network were recorded by the OBS array.

A thorough study of the earthquakes within the source region of the M_S 6.5 earthquake of November 4, 1977, those preceding it as well as aftershocks, is in progress. The objective is the detection of patterns in the seismicity which may be useful as precursors of larger future events. The aftershocks occurred initially about 40 km east of the epicenter of the main shock, then moved into the region to the west within a few days.

The microearthquake activity within the immediate vicinity of the epicenter (out to about 10 km), shows a distinct peak in January 1977, followed by low-level of activity in February, March and May 1978. The January peak near the epicenter is apparently associated with a surge of larger events to the southeast, in a section that had previously been inactive. Thus, a pre-shock swarm of activity occurred in a region larger than the particular subregion within which the main shock epicenter was located. The intervals of low levels of activity coincided with the occurrence of events with focal mechanisms apparently different from the usual ones, as indicated by SV/P amplitude ratios.

Further details of the double Benioff zone beneath Adak have been worked out on the basis of 205 carefully located earthquakes. The geometry of the two layers is now defined more clearly. Focal mechanisms for 15 events have been determined. Thrust mechanisms predominate in the depth range 45 to 60 km. The deeper events have strike-slip mechanisms, an unexpected result. The stress distribution within the subducting plate is certainly not fully known, much less understood. The most frequently occurring mechanisms show compressions along the arc from 45 to 60 km, lateral extension along the arc from 60 to 100 km and lateral compression along the arc from 100 to the termination of activity at 275 km.

Strain-release curves for each of the defined sub-regions have been plotted. The Gutenberg energy-magnitude relation and Benioff's simplified approach to calculating released strain from seismic energy have been used. Although both of these steps introduce uncertainties, the general picture of rate of strain release in each sub-region should be valid. Distinct differences in the rate of release exist, but the time base is still too short to permit an evaluation of the tectonic significance or diagnostic value of these differences.

Tiltmeter observations from Adak since 1975 have been analyzed and major effects of non-seismic influences identified. The tiltmeters have all been reinstalled and a definite improvement in performance achieved. No tilt signals of definite tectonic significance have been identified, but the capability to pull out such signals if they exist now seems available.

Hawaiian Seismic Studies
8-9930-01497

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Investigations

The project attacks the problem of determining the structure and tectonics of the island of Hawaii from seismic data and examining earthquake data for possible earthquake precursors and seismic precursors to eruptions. The project is responsible for continuing to process high quality earthquake data from the Hawaiian Volcano Observatory.

Preliminary monthly lists and plots of epicenters are now being generated for internal distribution. Hawaii is one of the most seismically active regions in the U.S., and maintaining continuity of high quality data analysis is an important part of monitoring trends and possible precursors preceding eruptions and earthquakes.

The project has also been instrumental in preparing an Eclipse minicomputer, its programs for handling earthquake data, and the accumulated Hawaiian data for self-sufficient use at the Hawaiian Volcano Observatory.

Results

Project efforts have been directed primarily toward preparation and programming an Eclipse minicomputer soon to handle all seismic analysis at HVO. An interactive system for storing, manipulating and displaying seismicity data on the Eclipse minicomputer is now under development. All Hawaiian earthquake data and many program modules are now available on the Eclipse. Presently, the Eclipse is able to playback and digitize the seismic traces, interactively pick arrivals, locate and plot epicenters, and select and manipulate subsets of arrival time and earthquake location data.

A new location program, HYPOINVERSE, was written to locate earthquakes within the Hawaiian and other networks. In addition to being small (from 22,000 to 28,000 words of core storage, depending on station capacity), the program uses a generalized inverse method which permits eigenvalve manipulation, principal error calculation, and output of actual information content of each station's arrival time. HYPOINVERSE also allows crustal models with layers containing linear gradients and an imbedded low-velocity zone.

An interactive hypocenter plotting program, HPLT was written to display Hawaiian and other earthquake data. The program plots hypocenters in map, cross-section, space-time and depth-time views. Data sets and plot parameters can be changed at will. The program has been used to plot the accumulated earthquake data from Kilauea Volcano and delineate seismically active magma conduits.

Reports

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Alaska Seismic Studies

8-9949-01162

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Investigations

1. Seismic data are collected and analyzed from a network of stations extending from western Cook Inlet to eastern Prince William Sound and as far north as the Talkeetna Mountains. This data establishes an important base of information for the study of the tectonic deformation and the related seismic hazards in southern Alaska.

2. With Funding from NOAA's Outer Continental Shelf Environmental Assessment Program (OCSEAP) seismic stations are operated from the Cordova-Hinchenbrook-Montague area on the west to Yakutat Bay-Harlequin Lake on the east. The northern limit of these stations is approximately 100 km from the Gulf of Alaska, and one station is located in Canada under a cooperative agreement with the Seismological Service of Canada.

3. Evaluate seismic hazards in the populated and developing areas of south-central Alaska, including the Anchorage, Palmer and Valdez areas and the Kenai Peninsula, as well as in areas of possible future development, such as the coastal region of the eastern Gulf of Alaska.

4. Carry out long-term seismic and crustal deformation studies in the Kayak Island-Yakutat seismic gap area in order to document premonitory earthquake phenomena prior to moderate-to-large earthquakes.

5. In cooperation with the Marine Geology Branch of Atlantic and Gulf of Mexico Geology, three ocean bottom instrument packages (OBIP) and two land-based units capable of detecting and digitally recording seismic events are being developed. The OBIP units will be tested off the eastern coast of the U.S. during the fall of FY79, and the two land units will be tested in California during the winter. We plan to deploy these units along the Eastern Gulf of Alaska during the summer of FY79 to improve our study of offshore seismicity in either the Pamplona Ridge-Icy Bay area or south of Yakutat Bay.

Results

1. All seismic stations were visited and put into working order. At 30 of the 50 stations newly designed and fabricated well-calibrated, auto-gain-ranging, crystal-controlled seismic station electronic units were installed. These new units are performing as expected.

2. The method for computing earthquake magnitude from coda duration has been modified to make it more self-consistent and useful for Alaskan data. The coda duration is now measured from the onset of S rather than P, and the distance factor has been reduced so that distant stations no longer over estimate the magnitude. The previously used formula is,

$$FMAG = -1.15 + 2.00 \log_{10} \tau + 0.007 Z + 0.0035 \Delta + C, \text{ where:}$$

τ is the coda

duration in seconds from P-wave onset to the point where the peak-to-peak trace amplitude on the Geotech film viewer falls below 1 cm.

Z is the depth in kilometers
Δ is the epicentral distance
C is the station correction

The new formula will be,

$$FMAG = -1.15 + 2.00 \log_{10}(\tau \cdot C) + 0.007 Z + 0.0006 \Delta$$

where τ is now measured from the S-wave onset time.

In addition, the location program HYPOELLIPSE now allows station weighting to eliminate stations with generally unreliable coda measurements.

3. The HYPOELLIPSE earthquake location program has been modified to allow the storage of data derived for individual stations used in locating a particular earthquake. Previously the only results of the location program that were stored were the hypocenter parameters.

4. Analysis was completed for earthquake data from October - December, 1977 and is nearly completed for the period January - March, 1978. A catalog of the data from the fourth quarter of 1977 was submitted as an open-file report.

Reports

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Puerto Rico Seismic Program

8-9950-01502

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Investigations

1. Continued operation of the 15-station Puerto Rico seismographic network to locate local and near-regional earthquakes.

2. Routine reduction of network data and preliminary analysis of earthquake locations for the time period between November 15, 1977, and January 1, 1978.

Results

Hypocenters have been computed for more than 400 earthquakes that occurred in the time interval between June 1, 1977, and January 1, 1978. A more uniform method, than was previously used, of assigning weights to the P- and S-phase data was employed for making these hypocenteral locations. The current results are very encouraging in that the earthquake locations show less scattering than indicated by the locations made from data prior to June 1, 1977. Of particular interest is a well-defined cluster of earthquakes north of Puerto Rico at about 19.2°N lat. and 66.5°W long., as well as several on-island concentrations of earthquakes. The seismicity to the northeast and southeast shows a tighter, more linear pattern than observed from earlier hypocentral locations. The master event method and J. W. Dewey's joint hypocenter determination (JHD) method will be applied to all of the "best located" Puerto Rico earthquakes to better define the overall seismicity pattern.

Seismic Data Libraory of WWSSN Seismograms

8-9930-01501

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This is a non-research project, and its main objective is to keep the WWSSN seismograms up to date and properly filed.

SUMMARY OF SEMI-ANNUAL TECHNICAL REPORT

Title: A Study of Earthquake Prediction and the Tectonics of the Northeastern Caribbean: An Experiment in Two Major Seismic Gaps

Principal Investigators: Dr. A. Murphy and Prof. L. R. Sykes

Contractor: Lamont-Doherty Geological Observatory of Columbia University

Date: 1 May 1978

Contract Number: USGS-14-08-0001-16748

Government Technical Officer: Dr. J. F. Evernden

Status of Seismic Network

A short-period, radio-telemetered network was constructed in the northeastern Caribbean with funds provided by three successive grants from the U.S. Geological Survey. At the present time (May 1978) the nine stations northwest of the Anegada Passage are in good operating order. Two horizontal-components have been installed; additional horizontal-components for the nine northwestern stations will be installed during the second half of the contract period. We will not have the necessary recording capacity until the digital event recording system is built during the next quarter. Two of the six stations southeast of the Anegada Passage are temporarily down.

Two SMA-1's have been installed; one on Anegada and the other on St. John. A borrowed SMA-1 is on St. Thomas.

A Sprengnether TS-250 timing system was installed at the central recording station in February 1978. A long-period seismometer vault has been constructed adjacent to the recording station. Installation of the equipment will begin in July.

Status of Routine Data Processing

A second data technician is being sought to increase the quality and quantity of basic information read from the Develocorder seismograms. This person will also handle computer processing and plotting responsibilities. A CRT computer terminal for the on-campus PDP 11/70 is now available close to the Develocorder reader. A second CRT computer terminal for the Columbia University IBM 360-91 is available in the next office.

Significant Observations for On-Going Research

The majority of the available research time for the first half of the contract has been spent investigating two areas within the network. A description of the observations obtained from these investigations and some background information follows:

The northeastern corner of the Caribbean plate was instrumented in mid-1975 as part of the U.S. Geological Survey's program of Earthquake Hazard Evaluation and Prediction. This area was selected because we felt that, based on previous studies, the area would produce significant information for the program in a relatively short period of time. The background scientific material in the proposals which support the Caribbean research effort clearly pointed this out. (Several of these previous Lamont investigations indicated that there were several seismic gaps within the area to be covered by our network. This includes the gaps associated with the Puerto Rico trench north of Puerto Rico and the Virgin Islands which do not have a proven potential for seismic hazard and the gap in the northern Lesser Antilles which does have a proven potential for seismic disaster, i.e., great earthquakes in 1690 and 1843.) Although not explicitly stated in the proposals or technical reports, we feel that the area definitely qualifies for the designation of an "area of intensified observation" as defined by the Japanese CCEP. This designation of area of intensified observation was applied unofficially to the entire area covered by the network, i.e., from eastern Puerto Rico into the northern Lesser Antilles. At this time we feel that two localities within the network qualify for the next CCEP designation of an "area of concentrated observation".

The first locality is about 50-60 km northwest of the island of Anegada near 64.5°W, 19.2°N. Detailed analysis of the seismicity data received since July 1977 clearly shows that there has been a marked change in the level of seismic activity. During the months July through October 1977 the LDGO network recorded an average of 7.6 events/day. (This count was obtained from a single station which operated continuously during this and later intervals without any significant changes in instrumental settings. A preliminary re-examination of data from mid-1975 to mid-1977 indicates that the average occurrence rate for the area covered by our network — 17.5° to 20.5°W and 64° to 66°W — during this time interval was about five events/day. A more detailed re-analysis of this older data base is underway.) About 1 November 1977 the rate of earthquake occurrence dropped to about five events/day. From that time to the end of the available seismicity record (May 15, 1978), the level of activity north of the network remained relatively low (Figures 1 and 2). The spatial pattern of seismicity may be interpreted in terms of Mogi's "donut" theory. (Regions preparing for large earthquakes tend to be relatively quiescent for some period of time prior to the event. The surrounding region becomes relatively active when compared to adjoining regions. This pattern spatially appears as a hole with an active ring around it, i.e., a donut.)

In addition to the above observations, this locality has not experienced teleseismic earthquake activity since at least 1950 (Figure 3) and was not active during the summer of 1976 when adjoining areas were active. During the last 25 years, no earthquakes with $m_b \geq 6.0$ have occurred in the region north of eastern

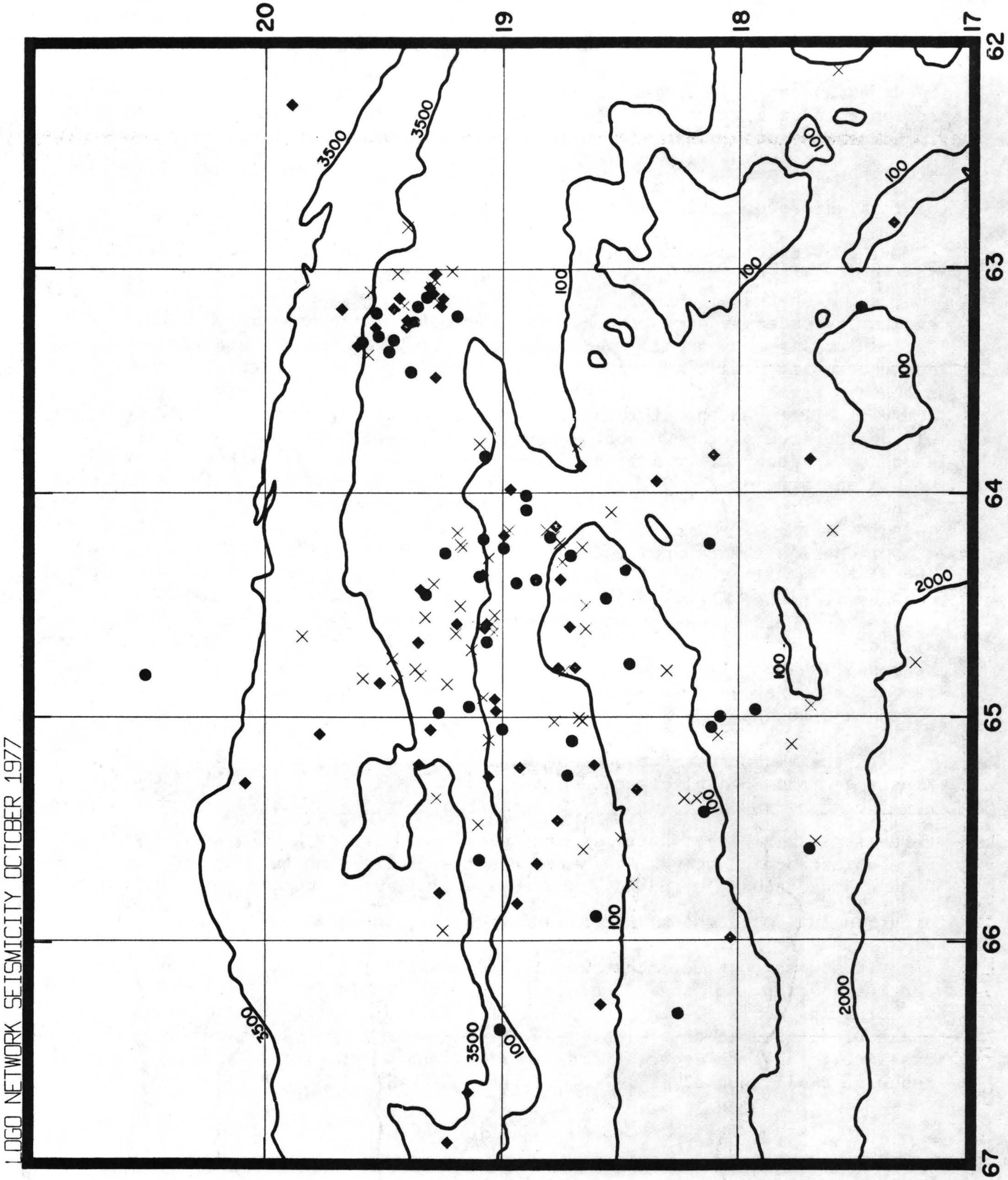
Puerto Rico and the Virgin Islands that is covered by our network, i.e., the region bounded by 18°N and 20°N and by 64°W and 66°W. (The average recurrence interval for earthquakes with $m_b \geq 6.0$ in this region during this century has been about 15 years.) Thus, we feel that the region near 64.5°W, 19.2°N may be in a quiescent period preceeding an $m_b \underset{>}{\sim} 5.5$ event.

The second locality is about 160 km north of St. Martin near 63.2°W, 19.4°N. Prior to 31 October 1977, the area within about 75 km of this point produced less than 1 event/month. On 31 October - 1 November 1977, 59 events, recorded by our network, were located near or associated with this second locality (Figure 1). The b-value calculated for this earthquake sequence using P-wave amplitudes is approximately 0.8. After this short, intense sequence, the region returned to approximately its normal level of activity. Between the 8th and 15th of February 1978, 30 more events occurred within the area of the October - November sequence. The b-value of this sequence is about 0.4. A marked drop in b-value, such as we have observed within the area of the October - November sequence, has been cited by several authors as precursory of moderate-to-large earthquakes.

If Mogi's theory applies, we can obtain an indication of the limits of the geographic location of possible future shocks by considering the following two observations. Between the 9th and 15th of February, 43 events occurred in an area to the southeast of the October - November sequence — definitely outside of the area of that sequence (Figures 1 and 4). The b-value of this third sequence is about 0.7. An additional half dozen events occurred in the last two weeks of February in an area abutting the northern edge of the October - November sequence.

In their abstract for the Spring 1978 AGU Meeting in Miami Beach, Price, Kisslinger and Engdahl describe a temporal seismicity pattern that appears to have been precursory to an $m_b = 6.5$ earthquake within their Adak network (low teleseismic activity; short, intense surge in microearthquake activity; relative quiescence; longer, less intense surge; increasing quiescence; an $m_b = 6.5$ earthquake). We have observed a similar seismicity pattern (except occurrence of main shock) associated with the second locality.

In summary, we feel that we have identified two localities qualifying for the description "area of concentrated observation" as used by the Japanese Coordinating Committee for Earthquake Prediction. We are not making an earthquake prediction at this time, however, since we do not have a long enough baseline of data to ascertain the implications of changes in the rate of occurrence of small shocks.



<u>Figure 1</u> Seismicity in the vicinity of the LDGO Caribbean Network for October 1977. Network sensitivity is nearly uniform between 18°-20°N and 63°-66°W. Note the uniform distribution of events between 19°-19.5°N and 64°-65°W. This uniform distribution is present in the monthly seismicity maps from July 1977 to October 1977. Also note the cluster of earthquakes centered near 63.2°W and 19.4°N. These are 34 of the 59 earthquakes that occurred on 31 October and 1 November 1977. (Less than 1 event/month occurred in this area prior to October). Solid symbols are better locations; all events are in the depth rangs 0-50 km.

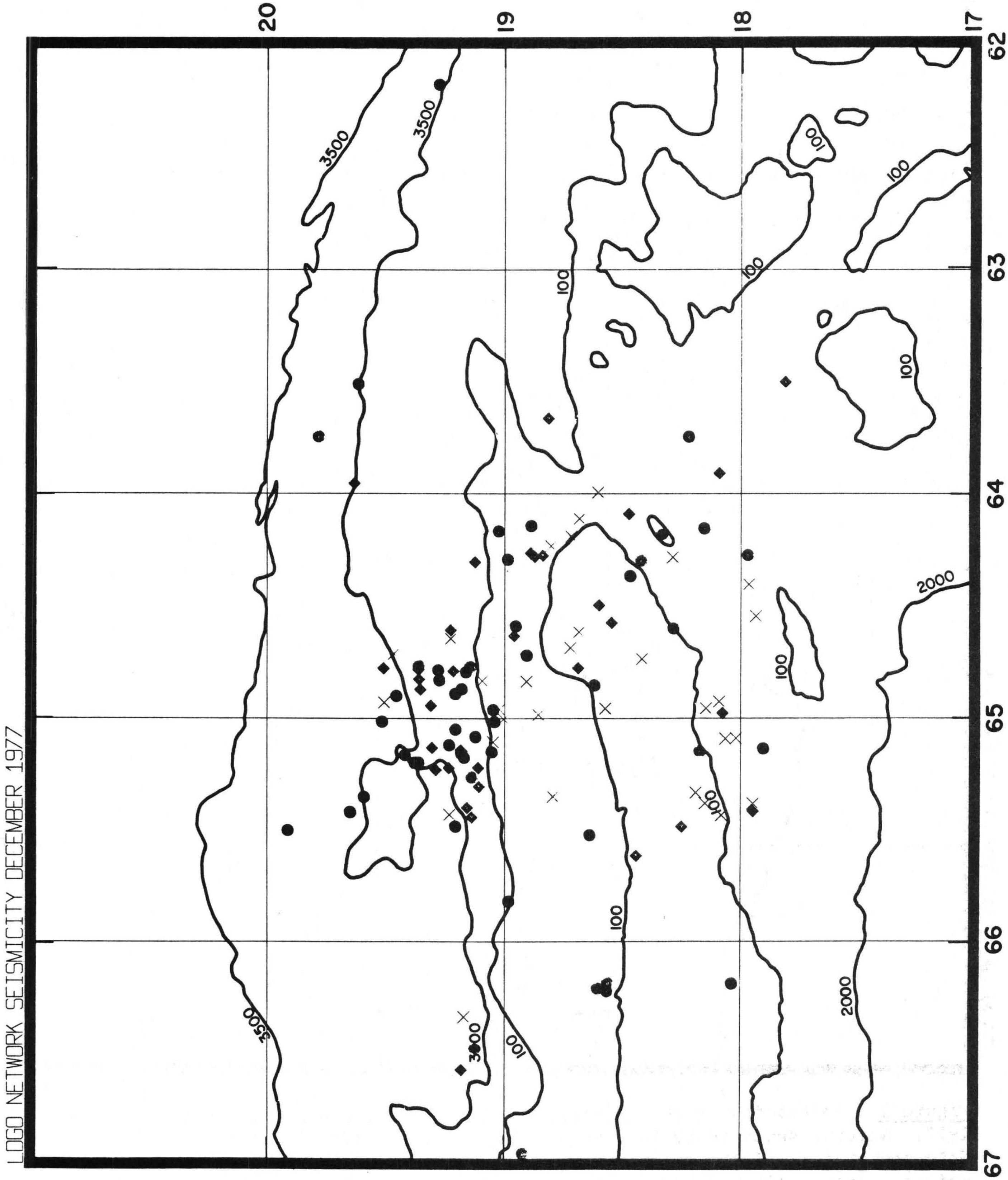


Figure 2

Seismicity for December 1977. Compare with Figure 1 and note the decrease in activity between 19°-19.5°N and 64°-64.6°W. Also note that there is no activity in the area of 19.4°N and 63.2°W.

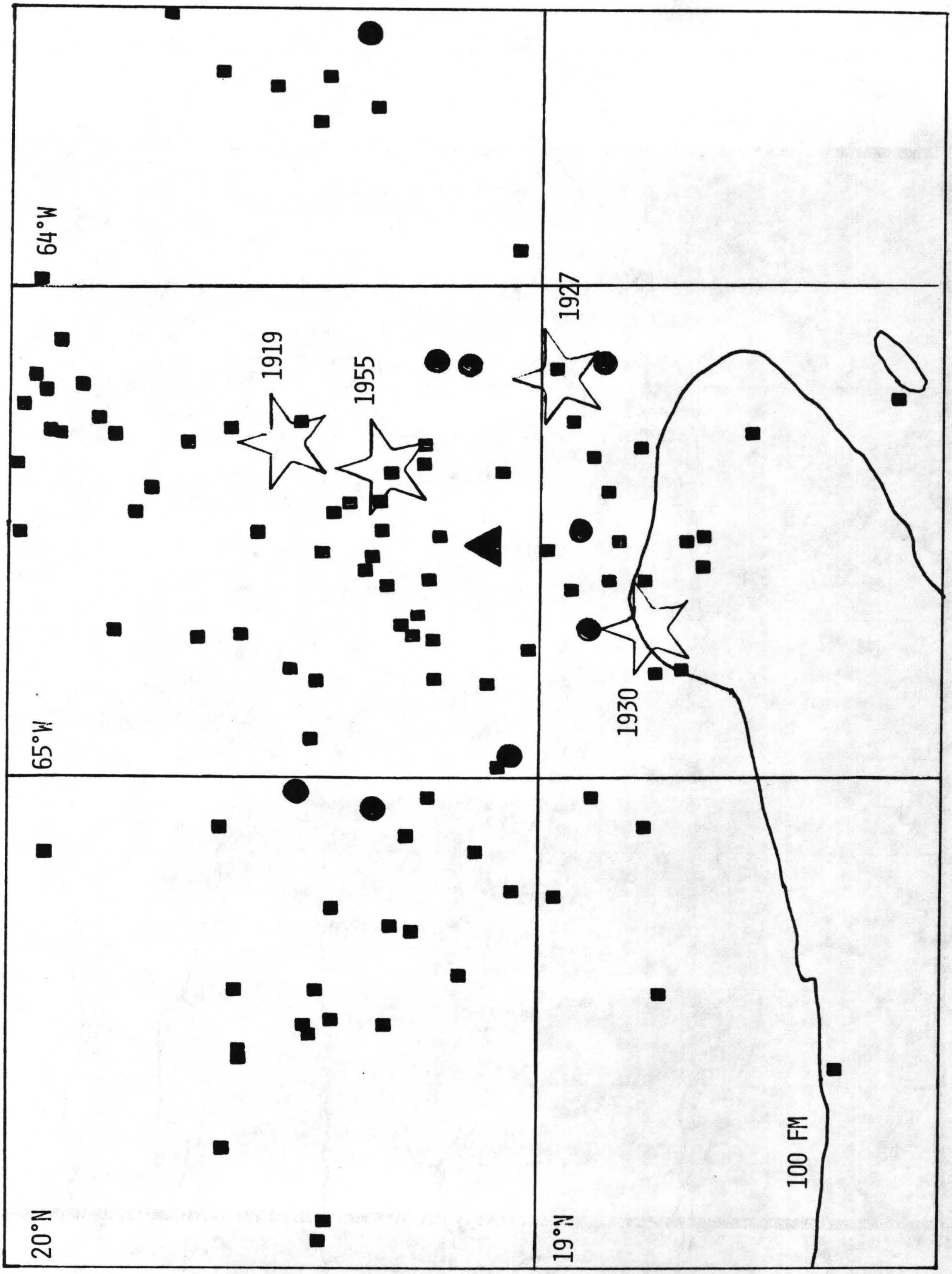


Figure 3

Teleseismic activity between 1950 and 1976 as reported by ISC. Squares are events between 1950 and 1973; circles are events after 1973; and the stars are all events since 1900 with magnitudes of 6.0 or larger. Note the lack of activity near 64.5°W and 19.1°N and its approximate correlation with the seismicity gap in Figure 2. There are indications that the teleseismic locations may be mislocated 0.1° to 0.2° too far south.

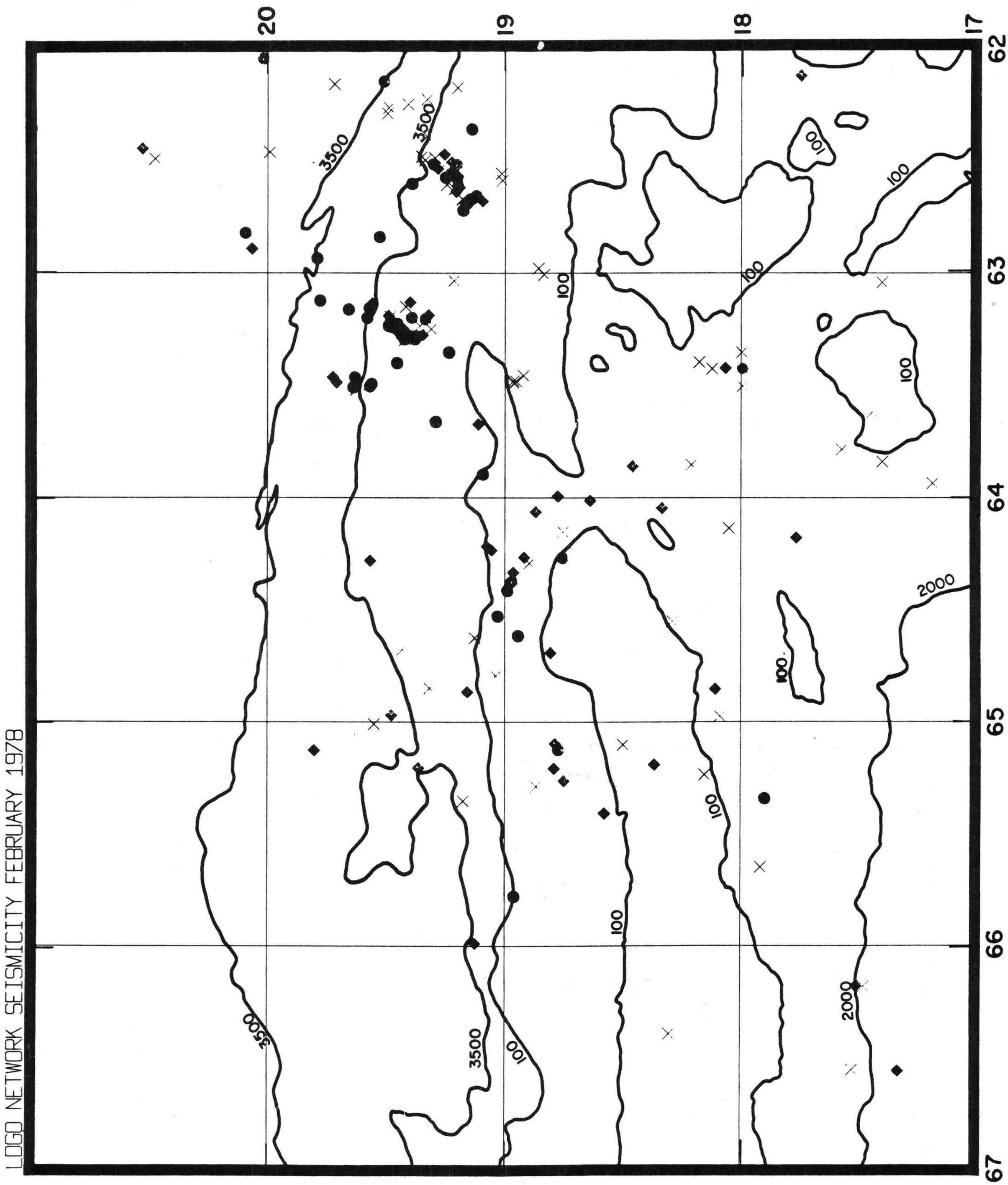


Figure 4

Seismicity for February 1978. The swarm activity has returned to the area of 63.2°W and 19.4°N as described in the text. Activity is very low between 19°-20°N and 64°-66°W and has virtually ceased between 19°-19.5°N and 64-64.6°W.

Northeast Seismic Network.

8-9950-01745

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Investigations

The Northeast Seismic Network which consists of approximately 85 seismic stations in 12 states is designed primarily to provide uniform seismic recording capability throughout the area of interest. The locations of stations in the network as of March 1978 are shown in Figure 1. Sub-network operators include:

Weston Observatory of Boston College
Massachusetts Institute of Technology
Lamont-Doherty Geological Observatory of Columbia University
Pennsylvania State University
Delaware Geological Survey

An agreement with the Earth Physics Branch, Department of Energy, Mines and Resources in Ottawa, Ontario, Canada, is currently being negotiated to provide several additional stations in Eastern Canada.

It is the objective of this project to promote cooperation among the various sub-network operators, to recommend courses of action to them, to recommend support for them as needed and to disseminate their epicentral information to federal, state and local legislative, planning and regulatory agencies.

Objectives

The objectives of the Northeast Seismic Network include:

1. The location and identification of sources of ground vibrations including information on latitude, longitude, origin times, depths and magnitudes for all events of $m_b \geq 2$.

2. The identification of zones of seismic activity and their relationship to geologic processes.

3. The evaluation of regional geologic strucure and tectonics using network results including fault plane solutions, travel time residuals, seismic moments, stress drops, attenuation determinations and crustal and upper mantle structure (from refraction data).

The ultimate goal of the network is to provide a realistic evaluation of the earthquake risk on a regional basis throughout the area and to disseminate this information to public and private planning and regulatory groups for appropriate action.

Results

The epicentral information collected by the sub-networks is synthesized and published in regional quarterly bulletins of the network. Cumulative epicentral information from the inception of the network through March 1978 is shown in Figure 2. which is taken from the latest quarterly bulletin.

In addition to the epicentral results, numerous scientific investigations have been carried out by investigators at the operating institutions. These investigations are published in _Science_, _Journal of Geophysical Research_, _EOS_ and _Bulletin of the Seismological Society of America_.

Publications

A _Quarterly Bulletin of the Northeastern United States Seismic Network_ is published by Weston Observatory of Boston College on behalf of NEUSSN. Ten (10) bulletins covering the period October 1975 to March 1978 have been published to date. The quarterly bulletins are distributed directly to over 400 addresses, including regulatory agencies, members of Congress from the affected areas and state legislators. As indicated above, research results of the individual sub-networks are published in scientific journals.

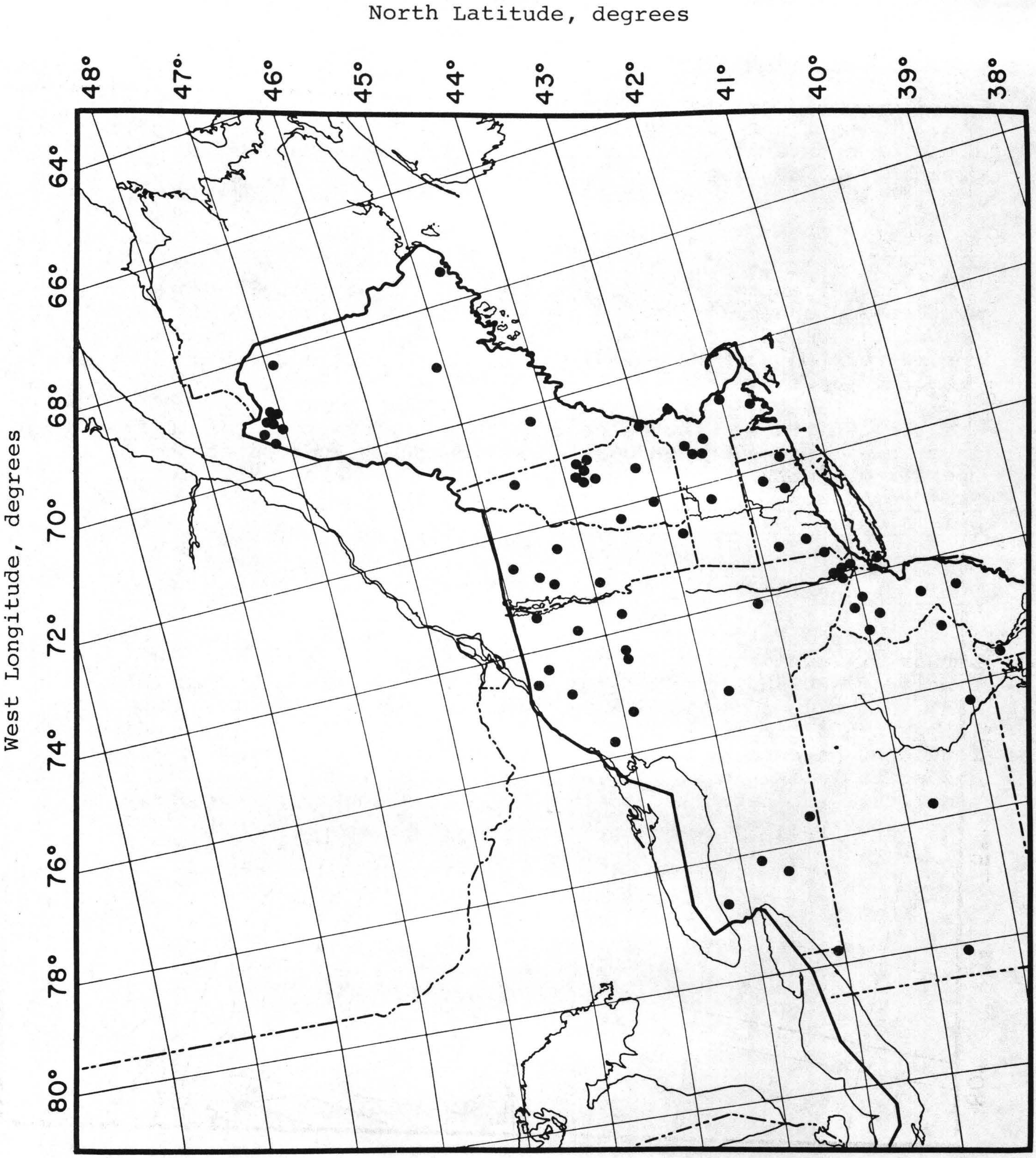

Figure 1. Seismic stations operating during the period January - March 1978

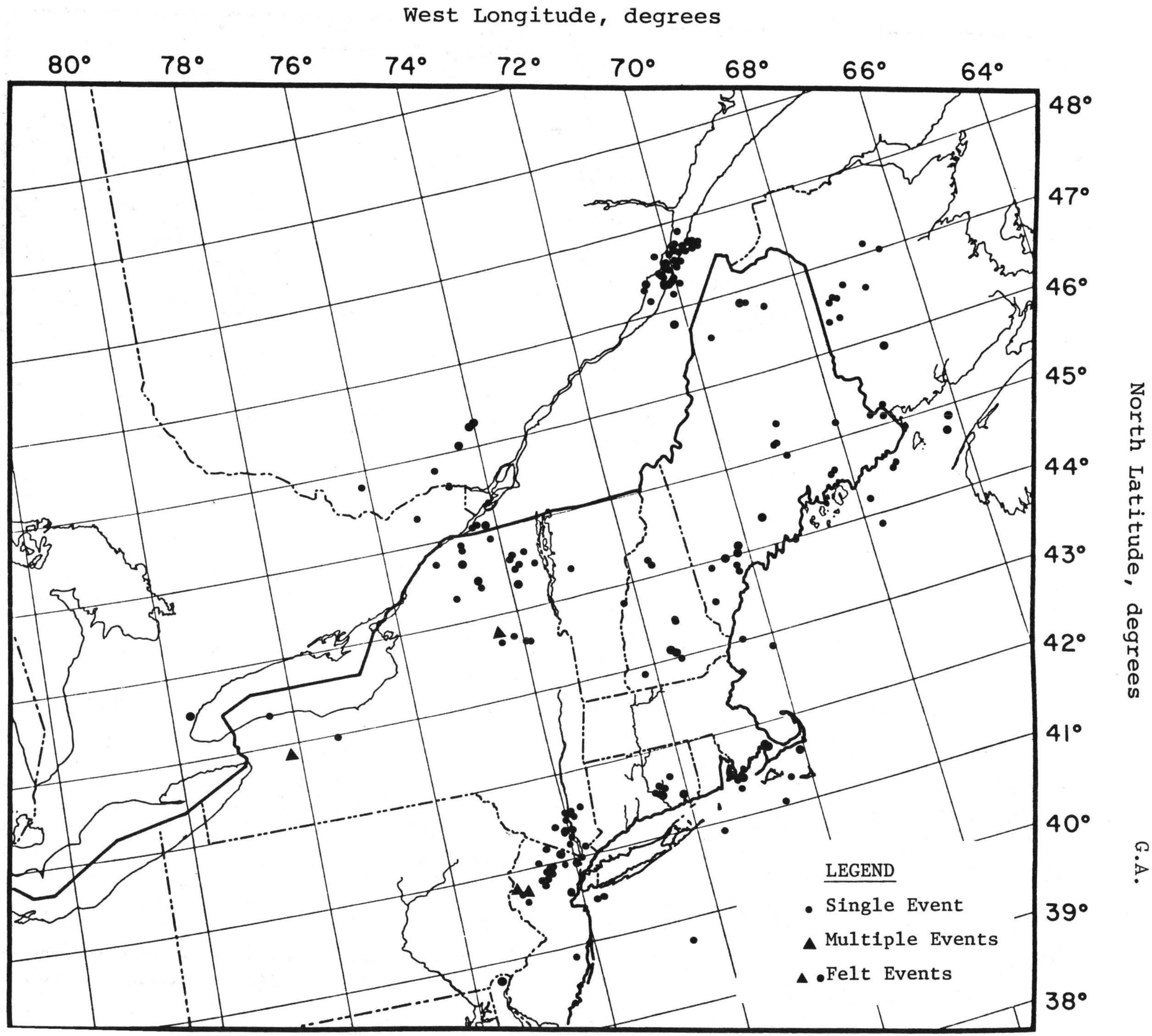

Figure 2. Earthquake epicenters during the period October 1975 - March 1978

G.A.

SEMI-ANNUAL TECHNICAL REPORT

Title: Induced Seismicity at Toktogul Reservoir and Seismotectonics of the Talas-Fergana Fault

Principal Investigator: D. W. Simpson

Contractor: The Trustees of Columbia University in the City of New York

Date: 15 October 1978

Contract Number: USGS-14-08-0001-16844

Government Technical Officer: Dr. Jack F. Evernden

Toktogul Dam is a 215 meter, reinforced concrete structure located in the narrow gorge of the Naryn River in Central Kirghizia, U.S.S.R. The major geological structure in the area is the NW-SE striking Talas-Fergana fault whose scarp fronts the main body of the reservoir (maximum capacity 19.5 cubic km) for 20 km on the southwest edge. The dam itself is 15 km downstream from the main body of the reservoir in the Naryn gorge which also appears to be a fault controlled structure. Just south of the dam the Kara Kul fault, which intersects the Talas-Fergana fault to the northeast of the dam, runs into the Naryn gorge. Both faults are seismically active. In the immediate area of the dam the largest earthquake was a magnitude 4.6 event in 1966. The largest earthquake in the surrounding region was the magnitude 7.5 1949 Chatkal earthquake on the Talas-Fergana fault 60 km to the northwest of the dam.

The project at Toktogul is a joint venture involving Lamont-Doherty Geological Observatory, the Institute of Physics of the Earth, Moscow, and the Kirghiz Institute of Seismology and is part of the U.S.-U.S.S.R. Exchange in Earthquake Prediction. The main American contribution is the installation of a radio-telemetered network of 7 high-gain, seismograph stations surrounding the reservoir to complement the existing, more widespread Soviet network. The Soviet stations will provide monitoring of the larger events within 100 km of the dam and continuity with the pre-impounding seismicity data. The American network will provide dense coverage in the most active region close to the dam and deepest part of the reservoir. The American system uses standard quadraphonic tape recorders, recording up to 6 (or 8) multiplexed FM seismic signals on each of the three tape channels. Timing information is recorded on the fourth channel and the system operates in an event triggered mode. Three of the stations consist of a 3-component high-gain set of instruments and a low-gain vertical. The network will be installed in October 1978.

Water level data and the catalogue of the Soviet network of earthquakes within 100 km of the reservoir from 1965 to 1977 inclusive have been analyzed. There was no dramatic increase in activity in 1974 when the reservoir was first filled to 80 meters. In fact, there appears to be a slight decrease in energy release over the whole area in mid-1974 which is almost certainly unrelated to the filling of the reservoir. The water level remained at a height less than 80 meters until early 1977 when there was an increase in seismicity rate in the immediate area of the dam as the water level first achieved and maintained a level of over 90 meters. Since late 1977 there has been a significant increase in the number of small earthquakes (maximum magnitude 1.5) close to the dam which were recorded by only one Soviet station. A very clear increase in this activity follows the first sustained filling to over 100 meters in October 1977. This activity continued into July 1978 when 3 MEQ-800 microearthquake recorders and 2 Soviet portable instruments were deployed in the vicinity of the dam allowing location of this activity for the first time. About 10 events per day were observed. Preliminary analysis indicates that the activity is occurring along the east side of the Naryn gorge both to the south and north of the dam. The events range from 0 to 5 km in depth and appear to lie on a fault plane steeply dipping to the southeast. The water level on the Talas-Fergana fault scarp has not yet reached 100 meters and no unusual activity is occurring there as yet. This fault probably poses the gravest threat to the safety of the dam. A substantial increase of induced activity on this fault as the water level rises to its final value of 215 meters could indicate that significant fault lengths are involved, capable of producing moderate sized events. Data on the historical seismicity in the region have been obtained from the Soviet "New Catalogue of Strong Earthquakes in the U.S.S.R." which, together with data from the NOAA epicenter file, will be used to study the seismotectonics of the Talas-Fergana fault and its relationship to other Central Asian structural features.

EARTHQUAKE RESEARCH AND NETWORK OPERATIONS IN THE INTERMOUNTAIN SEISMIC BELT--WASATCH FRONT

Summary of Annual Technical Report: April 1, 1978-September 30, 1978

USGS Contract No. 14-08-0001-16725

Investigators: R. B. Smith and W. J. Arabasz
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Salt Lake City, Utah 84112

Precursory Seismicity Patterns In the Wasatch Front and Utah Region*--Earthquake catalogs of historical, PDE, and Utah network data have been systematically examined for seismicity patterns before 72 mainshocks in the Utah region--including all 29 historical shocks ≥ intensity VI (M5.0) between 1853 and 1962, and all 18 main shocks ≥ M4.0 since 1962. Although foreshocks are apparent only for about 15% of the earthquakes, there is a remarkably consistent pattern of precursory quiescence within 50 km of each mainshock (Figure 1a). Such precursory quiescence is documented in the just completed catalog of Utah earthquakes, 1962-1978, and in the modern network data. We define the beginning of quiescence by the onset of the longest quiet period preceding the mainshock. The pattern of quiescence (Figure 1a) is more systematic than previously recognized -- and the time intervals involved are 1/2 to 1 order of magnitude longer than those recognized for active plate boundaries by Wyss et al (in press), whose precursor time-scale is nearly identical to that of Scholz et al. (1973). A regression of log t (days) on M_L, for 43 events of magnitude 4.0 or greater, yields the relation: $\log t = 0.4\ M_L + 1.1$. If the onset of precursory quiescence coincides with the onset of other long-term precursors, then our results have obvious implications for monitoring precursory phenomena in the Utah region--and suggest the importance of evluating precursor time scales by individual regions, especially in intraplate seismic areas. Results will be presented at the Fall 1978 AGU meetings.

Seismic Quiescence--The evaluation of seismic hazards on the Wasatch Front has been problematical because of the persistence of zones of earthquake quiescence extending 70 km north and south of Salt Lake Valley (Figure 1b). This pattern is well documented from data in the recently completed Earthquake Catalog of Utah, 1962-1978. The space-time diagram of earthquakes located within 10 km of the Wasatch fault demonstrates two prominent gaps in seismicity, each about 70 km long, north and south of Salt Lake City. The pattern was noted in our earlier publications but was not well defined until the new data set was prepared. Also from the new data, a time gap is apparent along a sector of the Wasatch fault north of Brigham City near the Utah-Idaho border. The pattern was heretofore thought poorly resolved because of poor-quality data, but now seems valid. The ten-year pause, then re-initiation of earthquakes along this segment of the Wasatch fault deserves attention because it may document the episodic nature of intraplate earthquakes peculiar to this area. It has more immediate implications if the quiescent period could be identified as precursory, with the 1976-1978 seismicity signalling the late stage of a cycle. It must be emphasized that these findings are new and must be critically evaluated; however, the data in Figure 1a indicate that several moderate-size earthquakes in the Utah region have been preceded by seismic quiescence of similar duration.

*Arabasz, W. J., and M. Griscom (1978). EOS, Trans. Am. Geophys. Union (in press).

Temporal Variations in Apparent-Velocities From Blast Monitoring--Periodic monitoring of large quarry blasts (averaging 40,000 obs) was reduced to once per week during this report period. Past monitoring initiated in October, 1974, has shown fairly stable apparent velocities as measured from five standard profiles across the Wasatch Front. To date no clear evidence of precursory velocity variations have been detected, but no earthquakes greater than M3.5 have occurred within 5-10 km of a profile. In June, 1978, however, an apparent velocity increase of +1.8% lasting $\sim$17 days, following a magnitude 2.7 event and coincident with several smaller earthquakes, was documented. This pattern of velocity increase following magnitude 2 to 3 earthquakes has been noted in our earlier reports but we did not consider them significant because we could not substantiate the velocity variation because of poor timing resolution. It now appears that increases in apparent velocities during and after earthquake sequences are systematic and reflect the earthquake process. We do not yet have an explanation of these results, but they may reflect strain hardening within crustal blocks following a large stress drop and the production of localized stress concentrations.

Published Results--

Arabasz, W. J., 1977. Time-varying source properties and use of initial P-wave pulse width for temporal monitoring (abstract): EOS, Trans. Am. Geophys. Union, 58, 1193.

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Smith, R. B., 1978. Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera; in Geol. Soc. Am. Memoir 152 "Cenozoic Tectonics and Regional Geophysics of the Cordillera", in press. (partial results from USGS project).

Smith, R. B. and Lindh, A. G., 1978. A compilation of fault plane solutions of the western United States: Ibid.

Smith, R. B., W. D. Richins, W. J. Arabasz, and D. J. Wechsler, 1978. An overview of the seismicity and tectonics of the southern Intermountain seismic belt from new array data with detail for southern Utah (abstract): Geol. Soc. Am., Abst. With Programs, 10, 238.

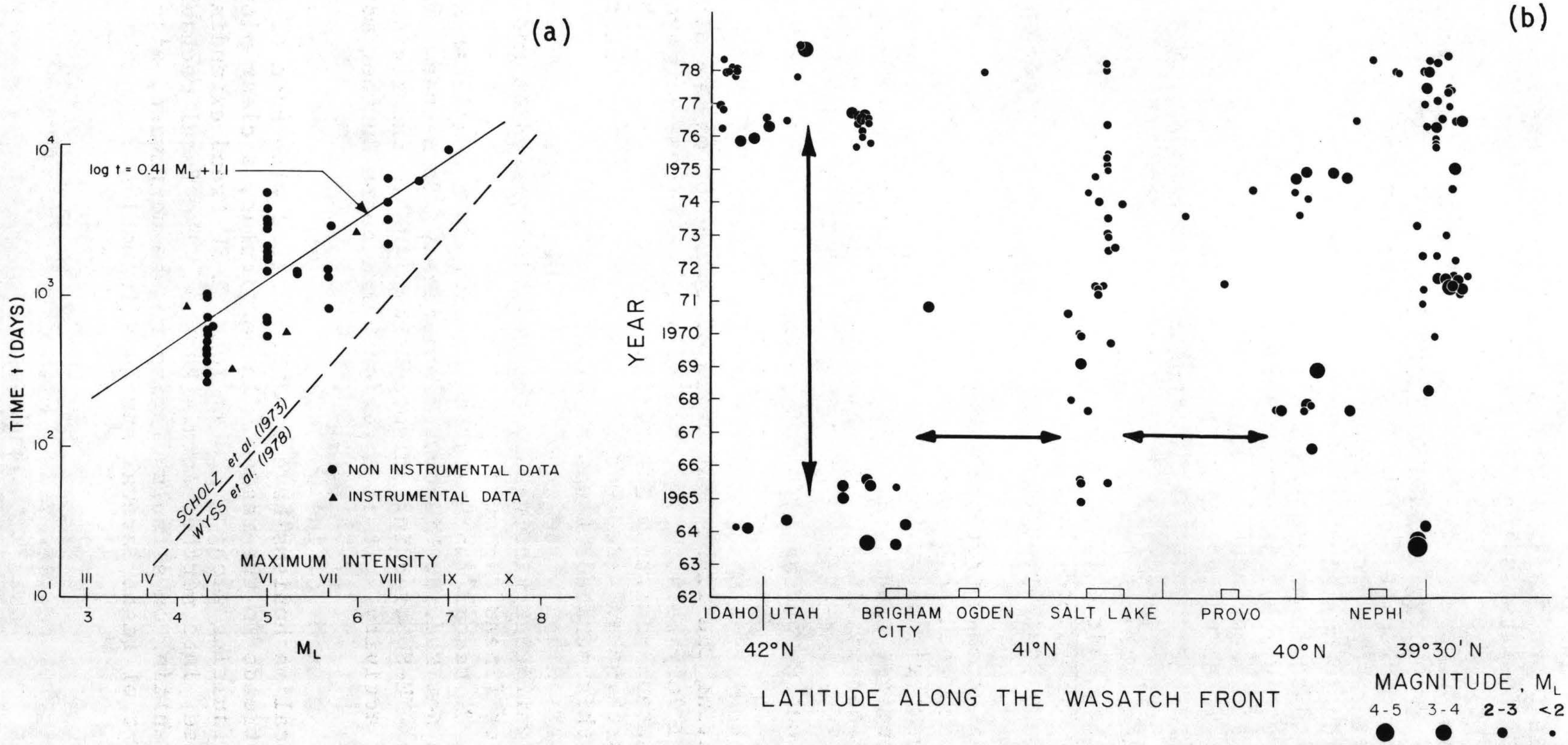

Figure 1: (a) Precursor time for onset of seismic quiescence versus magnitude (intensity) of mainshock. (b) Space-time distribution of earthquakes within 10 km epicentral distance of Wasatch fault, 1962 to 1978.

Earthquake Hazard Reduction in Southeast Missouri

FINAL TECHNICAL REPORT

Contract 14-08-0001-16708

William Stauder

Robert B. Herrmann

Saint Louis University

Summary

This research has as its purpose the monitoring of the seismicity in the New Madrid Seismic Zone, using the data from a sixteen station seismic array, and the conducting of research on eastern United States seismic sources by using array data and that from other stations.

Earthquakes which are recorded by the network in the New Madrid region are routinely located and the hypocenter locations are published in a quarterly network bulletin. During the first three quarters of this contract period 121 earthquakes have been located; 106 of these are located within a 1.5 by 1.5 area within the network. Another 323 earthquakes have been recorded by one or more stations, but not by a sufficient number of stations to make a hypocenter determination possible.

During the first four years of operation of the network, over the period 1 July 1974 to 30 June 1977, 731 earthquakes have been located, 616 of these occurring within the $1.5^{\circ} \times 1.5^{\circ}$ area of the array. Another 1116 earthquakes were recorded and reported in the quarterly bulletin during this period but not located.

Significant findings of the seismicity studies include the identification of linear segments up to 120 km in length of seismically active faults. A second feature of the region is a complicated seismic zone between New Madrid, Missouri, and Ridgely, Tennessee. This region offsets two NE-SW trending seismic zones, and is the region of the greatest seismic activity. It is a region which bears further more intensive study.

Focal mechanisms have been associated with some of the linear seismicity trends in the region. In particular, a clear picture has emerged of the faulting along a 120 km long NE-SW trend extending from Ridgely, Tennessee, into northeastern Arkansas. The focal mechanisms indicate reverse faulting on a fault dipping to the northwest, with a significant component of right lateral strike slip motion.

In another major study of earthquakes occurring in eastern North America large enough to excite usable long period surface waves, it has been found that most events have significant components of strike-slip motion. Specifically using P wave first motions together with amplitude and phase data from long period Love and Rayleigh waves, the focal mechanisms of twenty-two earthquakes occurring in eastern North America between 1962 and 1976 have been determined. The techniques used yield good results for events with bodywave magnitudes as small as 4.0. Eighteen of the events have depths between 5 and 16 km; fifteen have significant components of strike-slip motion; and for focal mechanisms having nearly horizontal pressure axes, seventy percent of the pressure axes trend NE or E. Though the earthquake sample may be biased toward the central United States, it is significant that no focal depths greater than 25 km have been encountered. A confidence factor is assigned to each focal mechanism for use in future tectonic syntheses.

National Seismic Network Feasibility Study
8-9920-02143

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Investigations

a. Estimate detailed cost and manpower requirements for instrumentation, installation, maintenance, and operation of two trial national digital seismograph networks. For each network, consider two data handling options: on-site recording and transmission of data to a central recording site.

b. Establish a rationale for the location of the stations in the networks and estimate P-wave detection thresholds for each network.

c. Develop a plan for the collection, processing, storage, and distribution of data from the national digital seismograph network.

Results

a. Two models for the development and operation of a national digital seismograph network were presented on June 29, 1978 to the National Research Council, Panel on National, Regional, and Local Seismograph Networks.

b. Modified versions of these models were discussed at a later meeting of the Panel on October 5, 1978.

Topical Seismicity Studies

8-9950-02092

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Investigations

1. Design of master U.S. earthquake data set and catalog, consistent with current data base management system (DBMS) philosophy.

2. Compile earthquake catalogs for southeastern United States for entry into the Multics DBMS (MRDS) as a prototype master catalog.

3. Compile and evaluate published focal mechanisms and in-situ stress measurements for North America.

4. Investigate the effects on the completeness of the earthquake catalog as a result of changing network detection thresholds.

Results

1. A preliminary data base, USEQDB, has been designed for the U.S. earthquake catalog. The data base is relational and is totally compatible with the SEDAS global seismological data base; both data bases are populated, accessed, and modified by Multics Relational Data Store (MRDS) software. USEQDB consists of some 22 relations that span most, if not all, significant attributes of seismic events. Only five attributes (see figure) are currently implemented: event, origin, maximum intensity, origin-to-focal mechanism, and focal mechanism. Twelve relations involve bookkeeping and referencing data. The remaining relations, when implemented, will constitute ways to hook into other data bases (for example, strong-motion peak parameters) or preserve statistical information on origin computations, principally from SEDAS.

2. FORTRAN and PL1 user application programs have been written to enable the general earth scientist to access the USEQDB without him having to know any details of the data-base structure or the MRDS data sublanguage (DSL). The programs are interactive with the user, prompting responses at the terminals. The following activities are now possible using these programs:

a. Selective searches of the data base on a variable number of attributes.
b. Creation of output data segments for use in other programs.
c. Creation of catalog listings which, when printed on a high-quality 132-character terminal, are camera-ready. Two types of catalog, hypocenter and focal mechanism, are alternative options.
d. Entry of a catalog data segment to populate the USEQDB.
c. Interactive entry of individual events in the USEQDB.

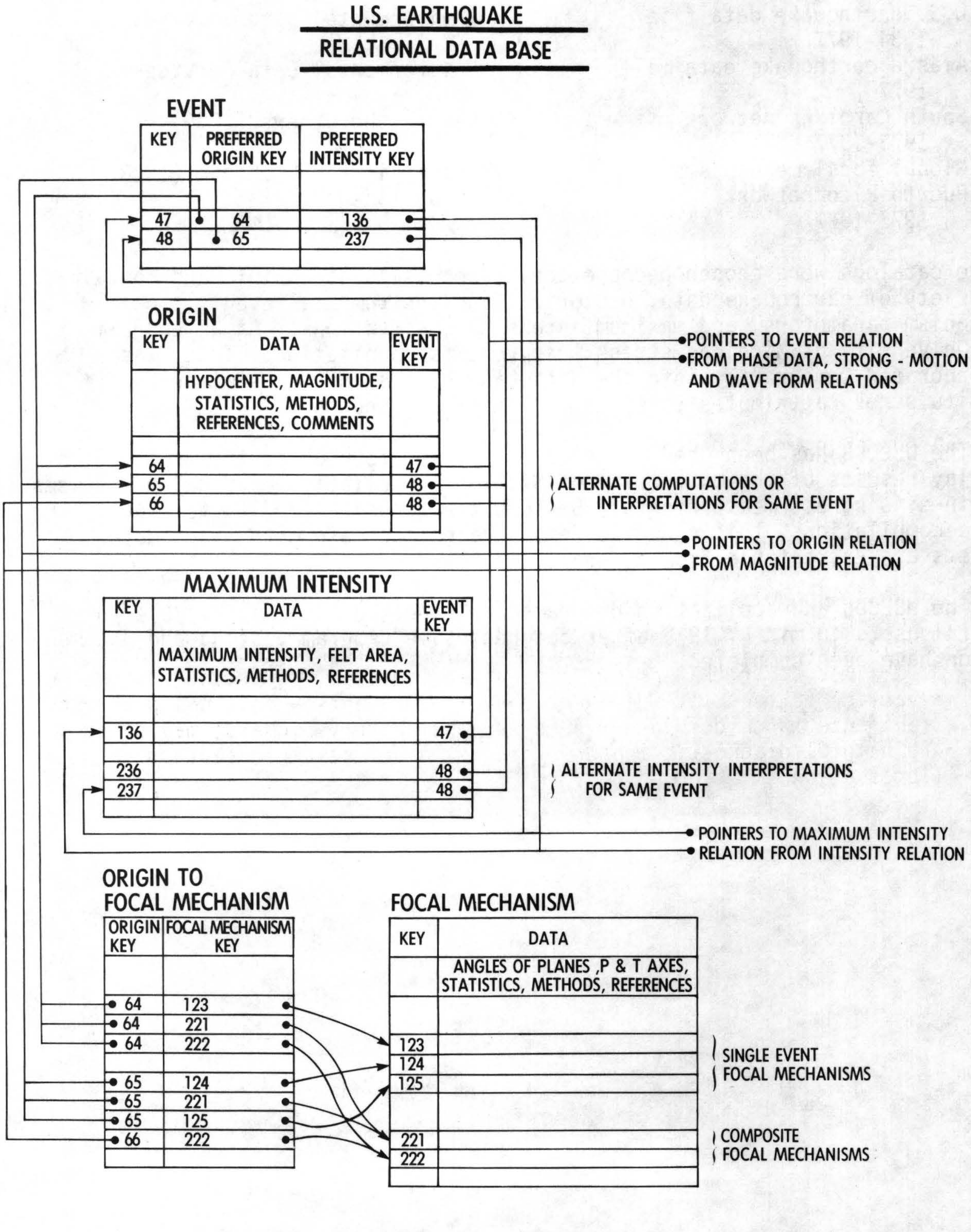
3. The data base has been populated from the following catalogs:

Southeastern U.S. 1754-1974	Bollinger (1975)
U.S. 1534-1974	Hays and others (1975)
U.S. earthquake data file 1534-1977	Environmental Data Services
Alaska earthquake data file 1977	Environmental Data Services
South Carolina network 1973-1977	Carver and others (1978)
Global focal mechanisms	University of Michigan (1978)
Puerto Rico network 1975-1977	Unpublished

These catalogs were chosen because they were easily accessible and contain a variety of earthquake data, historical and instrumental events, focal mechanism parameters, and maximum intensity observations. As an experiment, the University of Michigan stress measurements compilation, STRSS, was incorporated temporarily into the data base because of the similarity of in-situ stress attributes to focal mechanism attributes.

4. The USEQDB has been used to produce copy for four GP-series maps, which display results of the University of Michigan compilation of focal mechanisms and in-situ stress measurements. Besides the technical merits for publishing these compilations, this exercise demonstrates the ease with which data subsets are extractable from a large data base.

5. The USEQDB and application programs are expected to be accessible to general users in mid-FY 1979 after comprehensive program testing and documentation have been completed.


U.S. EARTHQUAKE
RELATIONAL DATA BASE
EVENT
KEY
PREFERRED ORIGIN KEY
PREFERRED INTENSITY KEY
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ORIGIN
KEY
DATA
EVENT KEY
HYPOCENTER, MAGNITUDE, STATISTICS, METHODS, REFERENCES, COMMENTS
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AND WAVE FORM RELATIONS
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FOCAL MECHANISMS
COMPOSITE
FOCAL MECHANISMS

UNIVERSITY OF SOUTHERN CALIFORNIA

Ta-liang Teng and Thomas L. Henyey, Principal Investigators

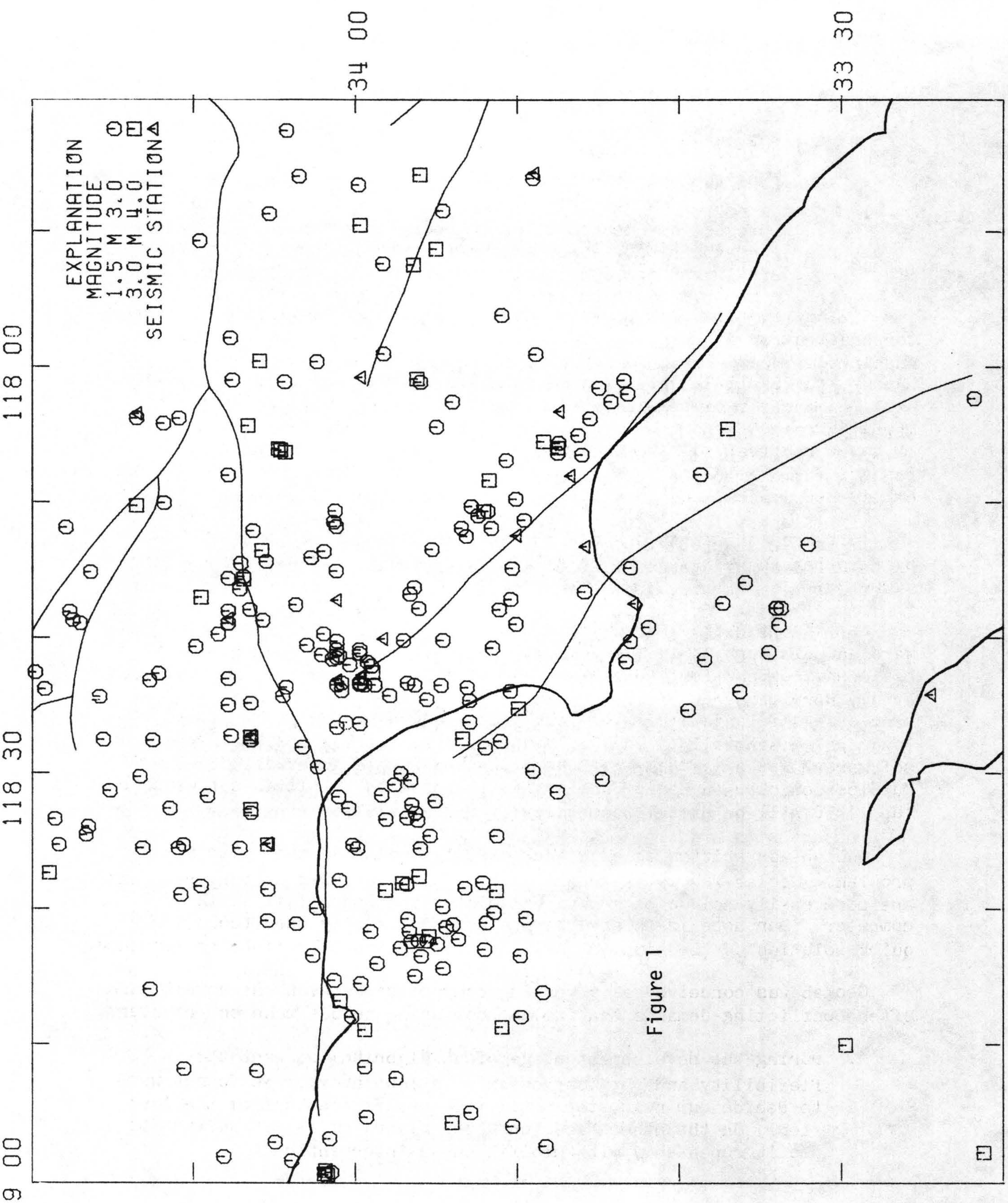
Contract No. 14-08-0001-16704

EARTHQUAKE HAZARD RESEARCH IN THE LOS ANGELES BASIN AND ITS OFFSHORE AREA

This project has concentrated on locating earthquake epicenters and examining their source mechanisms in the Los Angeles Basin and its offshore area with a goal of better understanding the tectonics of the region. A map of epicenter locations for the period 1973 to 1978 is given in Figure 1. A number of first-motion solutions have been reported in the 1978 technical report.

Earthquake epicenter locations in the offshore area should be considerably improved with the addition of new offshore stations on Santa Catalina and Santa Barbara Islands and a new land station in the Palos Verdes Hills area of southwest Los Angeles. These stations are in various stages of construction.

As a supplement to this research, Mr. Li-Sheng Huang (recently of the People's Republic of China), has been looking at precipitation patterns in arid areas of southern California. While the data is only preliminary at this stage, by comparing seasonal rainfall data from the past 90 years with the occurrence of large ($M > 6$) earthquakes along an arid stretch of the San Andreas, certain correlations have been observed. Most large earthquakes are preceded by a pattern consisting of a few years of below normal precipitation (drought) terminated by one or more consecutive seasons of heavy (above normal) rainfall. While this drought-above normal rainfall cycle can be seen at times other than prior to major earthquakes, it precedes, to varying degrees, all of the twelve $M > 6$ events. This new precursor evidence, when combined with other premonitory signals, may offer a helpful diagnostic measure that could be useful in earthquake prediction in arid regions.



EXPLANATION
MAGNITUDE
1.5 M 3.0
3.0 M 4.0
SEISMIC STATION
34 00
33 30
118 00
118 30
119 00

Figure 1

Minicomputer Processing for Research

8-9900-90034

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Six minicomputer systems have been ordered from the Digital Equipment Corporation for delivery in late December, 1978, to the University of Washington, Menlo Park, Caltech, CIRES, St. Louis University, and Lamont. A PDP 11/34 will be used to monitor data from local seismograph stations, detect earthquakes and store digital data for each event on magnetic tape. A PDP 11/70 processor will then be used to analyze the data interactively for routine bulletin preparation as well as for research. The 11/70 will also have the capability to process data from other instruments such as tiltmeters, strainmeters, etc.

Software for the 11/34 is being developed by Carl Johnson at Caltech by adapting the existing programs running there on a Data General Eclipse computer.

Software for the 11/70 is being developed under the auspices of Peter Ward and Jim Herriot in Menlo Park. The plan is to use Geolab as the basic environment for processing. Geolab is a command language developed by Jim Herriot over the last decade. It is ideal for interactive processing of large arrays of data and is a general purpose language--essentially a BASIC language for scientists. Much of the software for the 11/70 is presently running on the Honeywell 68/80 Multics Computer in Menlo Park and it is hoped that initial software for the 11/70 will be distributed by early Spring, 1979.

Geolab was written as an attack on the computer-human interface problem. Geolab was motivated in part by the scandal that many problems are more easily solved on a hand calculator than on a full scale computer. Our hope is to give people a set of easily used tools for quick solution of the simplest arithmentic to a complex plotting sequence.

Geolab was conceived as a working compromise between the several and often conflicting demands that we as tool using people make on computers:

1. During the development stage of an algorithm we want the flexibility and permissiveness of a laboratory. We do not want to decide our next step until the results are in from the last step. On the other hand, once our algorithm is set we want to use it repeatedly with minimal human intervention.

2. When doing stereotyped operations we need a few powerful operators to perform the whole task. To get a simple time-series plot should require just a few commands (which take care of all the details). On the other hand, we should not be barred from making our own decisions regarding details when custom work is required -- so-called "hands on" control.

3. We should be able to take advantage of the flexibility of interpreters (which can save much human time) as well as take advantage of the efficiency of compilers (which can save computer time).

4. We want a large repetoir of prefabricated ready-to-use tools. However, even if we had all 1000 of the tools voted most likely to succeed, someone would come along and want the 1001st. Accordingly, we need an easy way to fabricate new tools and so increase our vocabulary of operators.

SUMMARY

SEISMIC RISK IN THE ASSAM GAP

M. Wyss* and K. Khattri†

The seismicity data from 1825 to the present for the Assam (northeastern India) region show that seismicity rates there deviate from normal before and after major earthquakes. Along this 1,000-km-long section of a plate boundary, all shocks with magnitude $M > 6.6$ were preceded and sometimes followed by periods of significant seismic quiescence, and no such quiescence occurred at times other than before or after a major event. The most remarkable periods of quiescence lasted about 28 and 30 years before the two great $(M = 8.7)$ Assam earthquakes of 1897 and 1950. Other periods of anomalously low seismicity preceded main shocks of magnitudes 6.7 (in 1950 and 1975), 7.8 (in 1869), and 7.7 (in 1947), with durations of 6, 8, 23, and 17 years, respectively. These durations fit (with approximately the scatter of the original data) a published relation between precursor time and magnitude.

Since these changes of seismicity rate were observed at the edges of and within the Assam gap, defined by the 1897 and 1950 great earthquakes, it is likely that a future major or great earthquake in this gap will be preceded by seismic quiescence. Whether a preparatory phase for an earthquake has begun in the Assam gap cannot be stated for certain because of the changing earthquake-detection capability in the area and because of

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poor location accuracy.

As a result of the above-mentioned observations, a cooperative program to study the Assam Gap is developing. Leveling lines, gravity profiles, magnetic surveys, seismological and strong motion studies are planned. Some of the Indian institutions participating are Roorkee University, Indian Geodetic Survey, Indian Geological Survey, Indian Meteorological Department, National Geophysical Research Institute, and School of Earthquake Engineering of Roorkee.

Seismic Studies of Fault Mechanics

8-9930-02103

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Investigations

A detailed seismological study of crustal structure and seismicity of a 15 km long portion of the creep-active central segment of the San Andreas fault is currently being conducted using the 96 sensor Centipede micro-earthquake array. The objectives of the experiment are the determination of the three-dimensional velocity structure within and adjacent to a geologically and tectonically simple segment of the San Andreas system and the absolute location of earthquake hypocenters along that segment.

The study area encompasses the part of the San Andreas fault lying within Dry Lake Valley, Little Rabbit Valley and Rabbit Valley about 50 km SE of Hollister, California. This segment of the fault is characterized by a high creep rate and the occurrence of frequent small earthquakes. Earthquakes with $M > 4$ are unknown in the historic period. Because shear strain is not accumulating along this segment of the fault system, it is likely that the observed equilibrium between the driving forces and fault movement is maintained almost entirely by aseismic fault slip.

Results

Preliminary results from the Centipede array conclusively demonstrate that the seismicity associated with this segment of the San Andreas fault lies directly below the geologically mapped zone of recent movement (Figure 1). Routine earthquake locations reported in the USGS Bulletins are therefore systematically mislocated to the west of their true positions by 2-3 km in this region. Slip within the San Andreas zone, however, does not invariantly conform to the expected pattern of pure dextral slip on a vertical plane. For example, the distribution of P-wave first motions for the event illustrated in Figure 1 depart significantly from the "normal" pattern for San Andreas earthquakes. The symmetry of the travel time curve across the fault essentially rules out the possibility that the pattern, is an artifact that results from lateral refraction of raypaths.

Simple estimates of the compressional and shear wave velocities along the fault zone indicate that both Vp and Vs are very low. The average compressional velocity for the event in Figure 1 to stations along the fault is about 4.5 km/sec. Near surface velocities, as determined by a short, reversed refraction profile, are not unusually low which suggests that anomalously low velocities extend into the source region of the deeper earthquakes (8-12 km). A systematic analysis of the travel time data collected in this experiment will be attempted once work is completed on a new family of ray tracing programs.

Within the region there are also pronounced variations in the degree to which body waves are attenuated (Figure 2). Apparent Q_β values are highest ($Q_\beta > 100$) to the southwest of the San Andreas fault where granitic basement lies near the surface. Within 3 km of the fault zone the average Q_β is substantially lower (25-50), with the lowest Q_β values appearing to the northeast of the fault. At present, the physical mechanism responsible for these gross variations in Q_β remains unresolved, with differences in thickness and lithology of sedimentary rocks, and/or intrinsic properties of the fault zone being the most plausible candiate hypotheses.

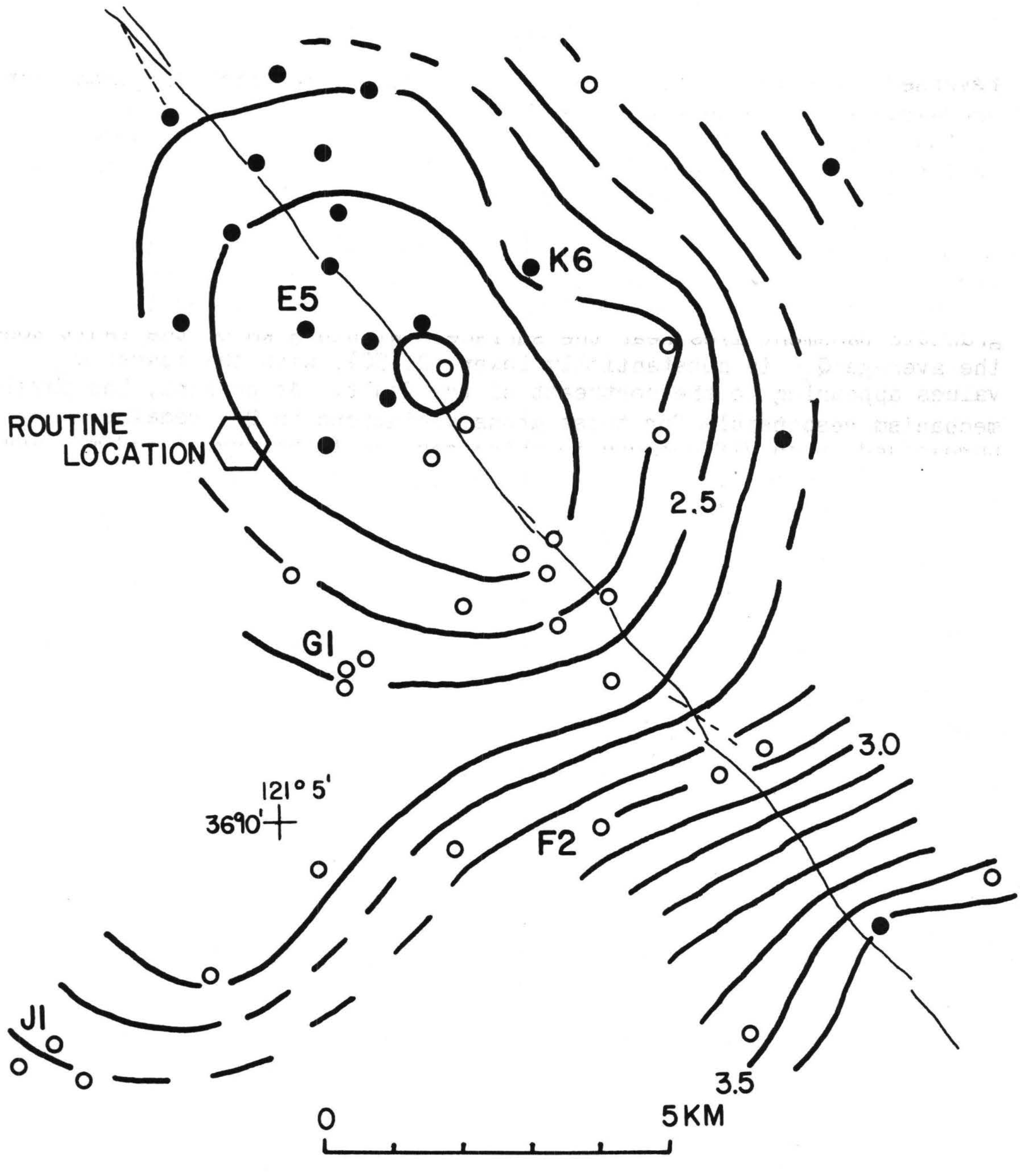

Figure 1. Contour map of P-wave travel times observed on Centipede for a M 1.4 event at 780907 0209. Contour interval 0.1 sec. Compressional P-wave first motion shown by solid dot. Dilitational first motion by open circle. Mapped strace of San Andreas fault after Brown (1970). Seismograms for named stations appear in Figure 2.

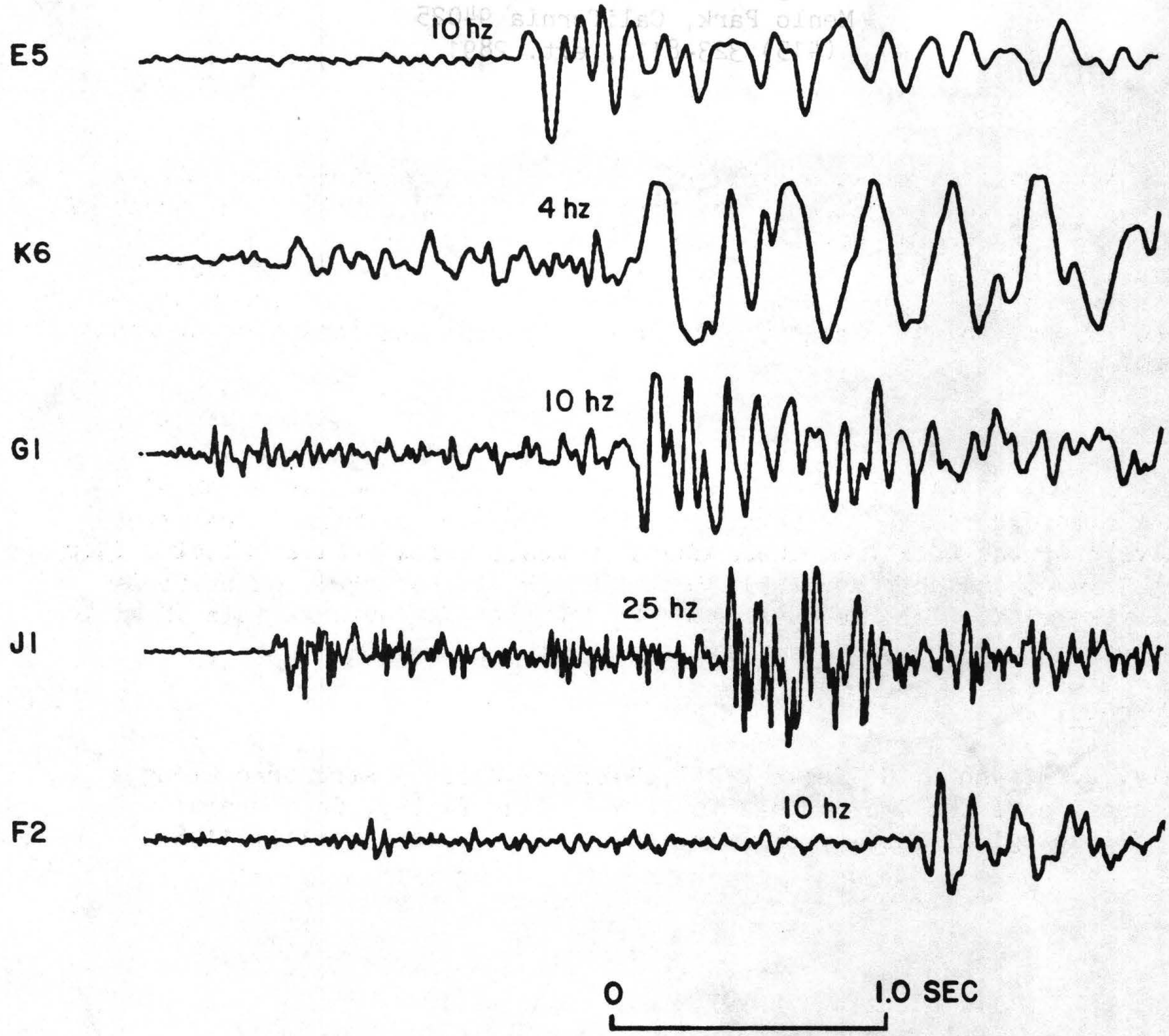

Figure 2. Horizontal component seismograms of ground velocity for M 1.4 event at 780907 0209. System response characteristics and amplification are identical for all records. Peak spectral frequency of shear wave appears above each trace.

Active Seismology in Fault Zones

8-9930-02102

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Investigations

Field work on a detailed seismological study of a section of the San Andreas fault zone centered around Dry Lake (approximately 50 km south of Hollister, CA) began late this summer. The report by W. L. Ellsworth summarizes progress in the passive part of this study. On October 15 the first two shots in the planned 8-to-10 shot active part of the study were fired in shot holes located within the fault zone and separated by about 10 km.

Results

Results from these 700 lb test shots will be used to decide on details (shot size, etc.) for the remaining part of the experiment. Preliminary analysis of the data from these shots suggests a low P-wave velocity (3.0 to 3.5 km/sec) within the fault zone similar to that reported by Healy and Peake (1975) for the fault zone in the Bear Valley area some 10 km to the north.

Reference

Healy, J. H. and L. G. Peake, 1975, Seismic velocity structure along a section of the San Andreas fault near Bear Valley, California: Seismological Society of America Bulletin, v. 65, p. 1177-1198.

Fault Zone Tectonics

8-9960-01188

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Investigations

1. Search for a downhole repetitive seismic source that can be employed to determine fault zone seismic velocity and attenuation properties by probing the region between the downhole source and a separate downhole seismic receiver. The motivation of this field experiment is to investigate the focal regions of some shallow earthquakes occurring in the San Andreas Fault zone in central California.

2. Centrifuge modeling of a strike-slip earthquake fault with a bend. The artificial gravity on a centrifuge provides gravitational body forces that improve the similarity of laboratory scale models to the real field situation.

3. Computation of the Kurile Trench-Hokkaido Rise flexure profile by an elastic - time-dependent plastic lithosphere model.

Results

1. Identified the Bolt Associates Model DHS-600 downhole air gun as suitable for initial experimentation of the fault zone seismic properties investigation. This downhole air gun has been proven to a depth of 300 m. Went through training course for air gun and air supply operations.

2. Located a medium capacity centrifuge (150 g at 8 ft radius, 60,000 g-lb) at Lockheed Sunnyvale plant. Made model of a strike-slip fault with a bend (8" x 10" x 10" model size) with a granular brittle modeling material (gypsum-sand mixture) that has a strength ~1/200 of natural rocks.

3. The flexure profile of the Kurile Trench-Hokkaido rise system has been fitted numerically to observational accuracy by an elastic - time-dependent plastic plate model. The elastic part of the constitutive relation is derived from seismology (relaxed moduli = 50% of the seismic values) while the strain rate dependent plastic part is derived from dunite deformation data extrapolated to the appropriate loading rates. The numerical fit of the flexure profile depends on a number of parameters such as the rock flow law parameters, the temperature distribution inside the lithosphere, and the state of pre-stress of the plate before it enters into the subduction zone. Two examples of fitting, one with Kirby - Raleigh flow-law parameters, and one with Carter - Ave'Lallement flow-law parameters are given. Because of the

non-uniqueness of the solution, conclusions regarding the values of the individual parameters cannot be drawn from the flexure profile alone.

Reports

Liu, H.-P. 1978, The structure of the Kurile Trench-Hokkaido Rise System computed by an elastic - time-dependent plastic plate model incorporating rock deformation data: Abstract submitted to AGU 1978 Fall Meeting.

California Institute of Technology

THEORETICAL STUDIES OF THE ROLE OF PORE FLUID IN PREMONITORY PHENOMENA

J. Bernard Minster and John W. Rudnicki

We have continued our numerical investigation of coupled-deformation diffusion effects for an inclusion model of faulting which was introduced by Rudnicki (1977). In particular, we have investigated the way in which dilatant hardening of the inclusion can transiently stabilize failure and give rise to a "precursory period" of initially quasi-static, but accelerating deformation. Calculations for the time dependence of strain in the precursory period were carried out by assuming a constant tectonic stress rate and an inclusion stress strain curve which consisted of a linear segment connected smoothly to a parabolic cap. Values were chosen for the constitutive parameters which were consistent with available laboratory and field data. This study was carried out in collaboration with J. R. Rice (Brown University) and included the investigation of the complementary stabilizing effect due to the time-dependent response of fluid-infiltrated porous material surrounding the inclusion (Rice and Rudnicki, 1978).

The calculations demonstrate that the stabilizing effect of dilatant hardening gives rise to an acceleration of inclusion strain (relative to the far-field strain-rate) which is far greater than that which occurs in the absence of pore fluids. Moreover, they suggest that a small amount of dilatancy can have effects of this kind. However, because the calculations predict that the decrease in pore fluid pressure from its ambient value becomes large (i.e. comparable to lithostatic pressure at 5 km depth) only very near to final instability, they provide no evidence of dilatancy induced alterations of seismic wave speeds. Nevertheless, the effects of non-linear fluid compressibility, which were neglected in these calculations, may contribute to lowering the pressure more rapidly.

Typical values for the calculated precursor times are on the order of hundreds of days for fault lengths of 1 - 5 km, values of the diffusivity of 0.1 to 1.0 m^2/sec, and a tectonic stress rate of 1 bar/year. Although the precursor time increases with fault size, it is not proportional to the square of the length, as might be anticipated for a diffusion controlled mechanism. Because the most rapid acceleration of strain occurs toward the end of what has been defined as the precursory period, observable effects will likely occur over a more shorter time scale. A minimum estimate of the precursor period on the basis of this analysis suggests that premonitory events are likely to be observed only a few days before earthquakes.

We have also begun investigation of the effects of coupled deformation - pore fluid diffusion for a very narrow fault zone to determine how predictions based on this model differ from those of the inclusion model. More specifically, the fault zone is assumed to be so narrow that it can be idealized as a planar surface and the constitutive law is specified as a relation between stress on the fault τ_{flt} and relative sliding δ rather than between stress and strain. Thusfar, we have studied the stabilizing effects due to the time dependent response of the fluid-infiltrated elastic material surrounding the fault by using a superposition of the solution by Rice and Cleary (1976) for a plane strain dislocation suddenly introduced into a Biot solid. The stabilizing effect results because the response of the surrounding material is elastically stiffer for load alterations which are too rapid to allow for fluid mass diffusion out of material elements ("undrained conditions") than for those which occur so slowly that the local pore fluid pressure is constant ("drained conditions"). The τ vs. δ relation is assumed to be parabolic and the far field tectonic stress rate is assumed to be constant.

An important result of the calculations is that the length of the precursory period (the period of self-driven accelerating slip prior to dynamic instability) decreases with increasing length of the fault for a plausible range of material parameters. This contradicts expectations based on naive dimensional considerations, but it agrees with a result obtained by Rice (personal communication, 1978) as the limiting case of a narrow inclusion with a fixed parabolic τ_{flt} vs. δ relation. Typical values of precursor time are less than a few days for fault lengths of 1-5 km., values of the field diffusivity of 0.1 to 1.0 m^2/sec, and a tectonic stress rate of 0.1 bar/year. The results are, however, sensitive to details of the τ vs. δ relation which are poorly known.

References:

Rice, J. R. and M. P. Cleary, Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents, Rev. Geophys. and Space Phys., 227-241, 1976

Rice, J. R. and J. W. Rudnicki, Earthquake precursory effects due to pore fluid stabilization of a weakening fault zone, in proceedings of Conference III, fault mechanics and its relation to earthquake prediction (convened under auspices of National Earthquake Hazards Reduction Program 1-3 December, 1977 at Stanford University), to appear in J. Geophy. Res., 1978.

Summary

Reporting Date: November 15, 1978

HETEROGENEITY, PORE PRESSURE AND DILATANCY IN CRUSTAL FAULTING

by

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Our research during the period 1977 through 1978 included studies of: (a) the process of dynamic faulting; (b) pore pressure distribution in the crust; (c) mechanics of aftershocks; (d) insitu permeability of fault zones; and (e) modeling of large fault zones.

(a) We have investigated details of the dynamics of faults with strongly variable stress and frictional strength. These factors are in all likelihood responsible for nonuniform fault slip, multiple events, random ground acceleration, and the earthquake frequency-magnitude relation. In order to obtain a full dynamic solution to greatly heterogeneous faulting we used a one dimensional continuum model in which stress and strength varied along the fault. We found that when the strength was sufficiently variable from place to place, the final stress was statistically at least as variable as the initial stress. We conclude, therefore, that spatially variable fracture energy may in fact be responsible for the heterogeneous nature of earthquake faulting. Nonunifrom stress by itself cannot maintain with time the heterogeneous nature of faults.

(b) Recent studies of the continental crust have resulted in velocity models which include one or more low velocity zones. The particular profile in the Gabilan range by McEvilly was considered, and an estimate of the required distribution of pore pressure with depth was obtained. It was found that the observed velocity profile could be explained by a high pore pressure zone at 5-8 km depth.

(c) The Nur-Booker diffusion theory of aftershocks is reexamined in the the light of a recent solution to the coupled problem of an edge dislocation in a fluid-satruated medium. Numerical techniques are used to extend the theory to a distribution of edge dislocations. Time dependence of the aftershock rate was examined for a number of slip distributions. All were found to obey Omori's law.

$$N = \alpha t^{-\beta}$$

It was further found that β took on only two values. For finite slip zones $\beta = -1$ and for semi-infinite slip zones $\beta = -0.5$. β is completely independent of the detials of the slip distribution; it depends only on whether or not the net slip over the zone is zero or nonzero.

(d) Subsurface observations of water, oil, and gas occurrence and flow characteristics indicate that flow near faults is anisotropic. The nature of fault influence on flow characteristics appears to depend on whether the rock is sedimentary or crystalline. For sedimentary rocks, at least one side of the fault plane is usually observed to be a barrier to fluid flow. In both sedimentary and crystalline rocks, faults are seen to provide channels for fluid flow parallel to the fault plane. Aydin's observations on faulting in sandstone seem to explain the barrier property of sedimentary rocks, while the observed fracturing near faults explains the presence of flow paths parallel to the fault plane.

(e) Some simple aspects of strain accumulation along a strike slip plate boundary are examined. In two dimensions a constant stress boundary condition confines all strain changes during an earthquake cycle to within a few tens of kilometers of the fault. In contrast, a constant plate speed condition results in a small but varying component of uniform shear out to great distances from the fault. For the San Andreas fault, a plate speed condition seems most appropriate, suggesting that shear strains on the order of 4-9 x 10^{-6} accumulated and were released out to distances of hundreds of kilometers during the 1906 San Francisco earthquake cycle.

THE MECHANICS OF CRUSTAL FAULTING

Principal Investigators: A. M. Nur, Stanford University
D. M. Barnett, Stanford University

Contract No: 14-08-0001-15260

Report Date: October 26, 1978

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1. Strike-Slip Faulting in a Downward Varying Crust

Both laboratory measurements and in-situ velocity data indicate that the rigidity of the upper crust increases monotonically with depth. The shear modulus variation with depth is reasonably well-approximated by the relation

$$\mu(x) = \mu_{\infty}(1-\theta\, e^{-x/x_o}).$$

Using this relation, a model for a long strike-slip fault was studied and the free surface deformation and fault stress drops were calculated for typical faulting events and then compared with results for a uniform crust ($\theta = 0$). The results of this investigation suggest that the rigidity change with depth can modify faulting characteristics sufficiently to affect conclusions implied from data inversions based on uniform crust models.

2. Strike-Slip Faulting in a Horizontally Varying Crust

Variable horizontal crustal rigidity was modelled by considering a half-space containing a series of vertical laminated layers of different thicknesses; within a layer the crustal shear modulus was assumed constant. Thompson-Haskel layer matrices were used to represent exact solutions for the inhomogeneous faulted half-space.

If the faulted zone is surrounded by a stiffer symmetric crust, the compliance of the fault zone must be an order of magnitude lower than its surroundings to yield deformation fields significantly different from those predicted using uniform crust models. If the weaker fault zone is surrounded by a stiffer, but non-symmetric crust, asymmetries in the predicted deformation fields occur. The results clearly indicate that inversion of surface data assuming a uniform crust could yield somewhat spurious results for depth of slip regimes. More complex fault models, including the introduction of a parallel non-active secondary fault, were also studied; such models showed that local strain amplication ten times greater than that predicted from uniform crust models could be predicted.

3. Elliptical Heterogeneity in a Constant Stress Field

A model was developed to study (approximately) the effect of a finite-sized elliptical inclusion on surface deformation. The inclusion perturbs a remote uniform anti-plane stress field. Although crude, this simple model indicates that finite crustal non-uniformity can lead to anomalous surface displacements, i.e., these considerations may be a potential cause for noise in surface measurements.

Topical Studies in Geophysics

8-9920-00393

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Investigations

Topical Studies in Geophysics consists of two subprojects: (1) a study of crustal structure of the Southern Rocky Mountains and (2) a study of the root of the Sierra Nevada. With the completion of the report by Claus Prodehl and L. C. Pakiser on the first subproject, my study of the Southern Rocky Mountains has been completed, except for possible final revision of the manuscript following review by the *Bulletin* of the Geological Society of America. James N. Brune (University of California, San Diego), Bruce Julian, and I are continuing our study of the Sierra Nevada. This study will be completed on or before February 28, 1979.

Results

Brune and I have interpreted P_n waves generated by aftershocks of the September 1966 Truckee, California, earthquake (magnitude 5-3/4) and recorded by the California Institute of Technology in the Sierra Nevada. Stations at Woody, Isabella, and China Lake lie approximately on the arc of a circle 450 km south of Truckee. The P_n arrivals at Isabella were delayed 0.8 sec with respect to those at Woody and China Lake, suggesting that the crust is about 11 km thicker at Isabella. P_n waves in the Sierra west of Tinemaha, about 300 km south of Truckee, were delayed by about a second. The greatest P_n delay, in the high Sierra west of Lone Pine, was 1.5 sec, suggesting crustal thickening of about 21 km in relation to the foothills to the west and the basin ranges to the east. A crustal thickness of 50 km or more beneath the Sierra seems probable. This result implies that the waves generated at the Nevada Test Site and arriving early at stations in the Sierra Nevada, which were identified by Dean Carder and his co-workers as P_n in 1970 and 1973, actually bottomed within the crust rather than in the upper mantle. Our results generally support the model proposed by Jerry Eaton in 1966.

Reports

Prodehl, Claus, and L. C. Pakiser, Crustal structure of the Southern Rocky Mountains from seismic measurements: approved by the Director and submitted to the *Bulletin* of the Geological Society of America.

Pakiser, L. C., and James N. Brune, Root of the Sierra Nevada (abstract): approved by the Director and submitted to the American Geophysical Union for publication in *EOS* and presentation at the 1978 Fall Meeting in San Francisco.

Mechanics of Geologic Structures Associated with Faulting

8-9960-02112

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Investigations

A. Pollard and Segall

1. Search for and begin mapping a region in the Sierra Nevada batholith which displays small faults in granitic rock.

2. Develop a critique of fault models, especially those employing elastostatic theory.

3. Derive a fault model which accounts for the complete interaction of several discrete faults or fault segments.

B. Johnson and Fletcher

Continue analysis of folding of rock strata in preparation for a U.S.G.S. Professional Paper on folding and density instability.

Results

1. The region along Bear Creek near Kip Camp in the Mt. Abbott Quadrangle was selected for detailed investigation of small faults in the Edison Lake Pluton. These faults display strike slip of 0 to 10 m, are 1 to 10 mm wide, have multiple echelon segments, and contain some quartz and epidote mineralization and minor granitic gouge. A program of field mapping, sampling, and microscopic study was initiated.

2. A solution for a traction-free elliptical hole in an infinite elastic medium subject to uniform stress at infinity has existed in the literature since the 1920's. This solution is quoted in standard textbooks on elasticity theory (e.g. Timoshenko and Goodier, 1970, p. 193) and rock mechanics (e.g. Jaeger and Cook, 1969, p. 253), but it is incorrect. In the limit as the hole becomes a slit and the stress a pure shear, this solution is used commonly to model faults or slipped portions of faults. The proper stress state is obtained, but the only displacements at the slit wall are parallel to the slit. In the correct solution, displacements at the slit wall include perpendicular components, the slit walls are pressed together, and the slit plane rotates.

The boundary conditions on the slit wall are violated if the walls press together. This problem was overcome for the case of single slit in a solution due to C. Berg (Journal of Geophysical Research, 1965, p. 3447) by introducing a uniform compressive stress within the slit, sufficient to keep the walls apart. The introduced compressive stress is small, but could in principle increase friction and promote fault stability.

3. Observations over a wide range of length scales demonstrate the ubiquity of echelon fault patterns. These patterns may develop where a planar fault breaks down at its periphery into discrete segments which propagate into a new orientation. The peripheral region subjected to mode-III loading is apparently most susceptable to this process. Field examples from granitic rocks of the Sierra Nevada illustrate the echelon patterns and the nature of rock deformation between segments where tension gashes and secondary faults are observed.

To study multiple fault segments we need an elastic solution for several slits, but this is not available in the literature. We have used the Schwarz Alternating Method to derive a solution for an arbitrary number of non-intersecting slits at arbitrary locations subjected to a uniform regional stress. For closely spaced echelon slits the problem of walls pressing together is severe and significantly effects the stability of the system and the local stress state. An examination of these effects for reasonable fault geometries is in progress.

4. Most analyses of folding have been completed and the first draft of a Professional Paper is finished. A revision is in progress. One new result concerns the transition from similar to concentric folds. Laboratory experiments with a three member multilayer, comprised of two stiff layers and a soft interbed, indicate that the transition occurs at lower limb dips when the interbed is thinner. Theoretical analysis, exact to second order, generalizes the laboratory results. It indicates that for a thick or soft interbed the transition to concentric folding occurs at great limb dips (20 to 25 degrees); whereas for thin or stiff interbeds the transition occurs at limb dips of a few degrees.

<u>Reports</u>

Segall, P., and Pollard, D. D., 1978, Two mechanism for fault stability (abs.): EOS (Transamerican Geophysical Union), v. 59, no. 12 (in press).

Coherent Seismic Wave Analysis

8-9930-02296

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Goals

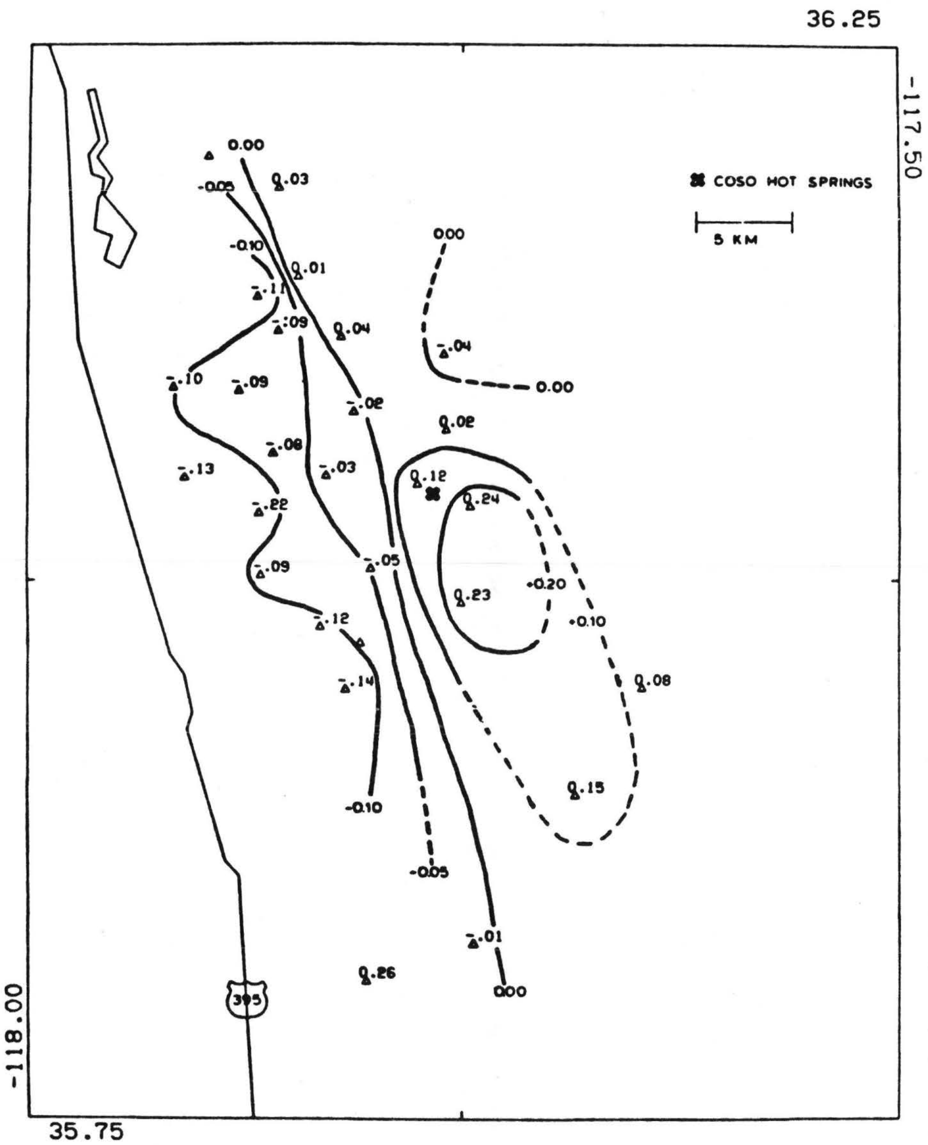
Our goal is to observed and interpret temporal and spatial velocity variations in the crust. Ultimately, when combined with other geophysical observations, a local spatial velocity anomaly might be interpreted in terms of crustal thinning, presence of partial melt, incompetent rock related to a fault zone, etc. Temporal variations of seismic velocity are more difficult to observe. However, extensive laboratory evidence and limited field results suggest that an observation of *in situ* velocity change, if carefully enough controlled, could properly be viewed as evidence of *in situ* stress variation.

Investigations

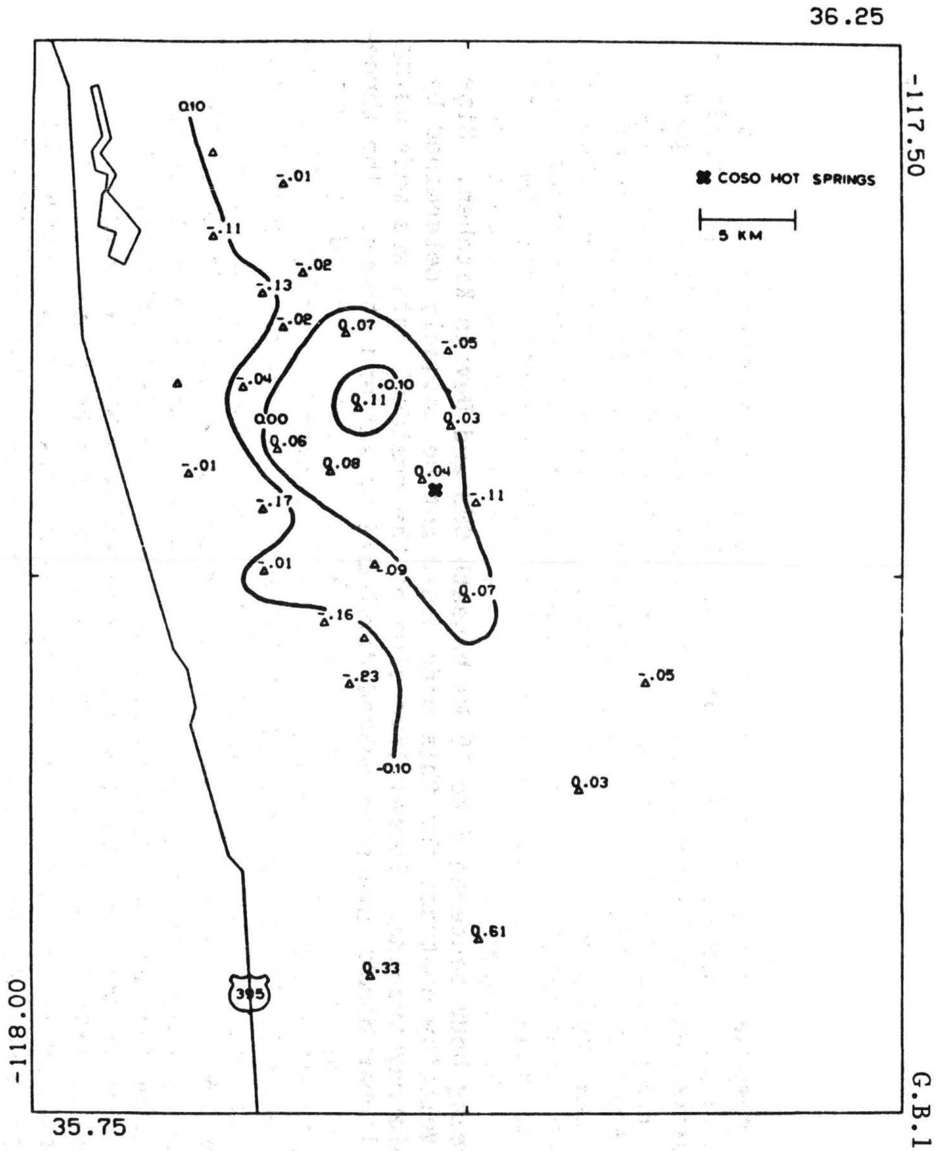
In our last report we described an attempt to detect a nearly vertical reflection off the Moho from a Vibroseis source. A 64-element linear array (Centipede system) was installed at Williamson Valley in the Gabilan range east of Monterey Bay. The Vibroses source was operated as part of Tom McEvilly's deep reflection velocity study. The data was successfully tape recorded and digitized. Stacking and pulse reconstruction by cross correlation were applied to the 30 second duration Vibroseis chirp, using software developed for this purpose on an Eclipse minicomputer. The minicomputer was not equiped with a hardware array processor. Standard reflection survey procedure employs a hardware stack (geophone grouping) and a real-time hardware correlator or array processor for data reduction. While we were able to reproduce each step of this procedure with software, the speed and memory limitations of the bare minicomputer made this approach impractical. We conclude that the loss of flexibility resulting from hardware pre-stacking and correlating prior to recording is greatly outweighed by the advantage of processing efficiency thus obtained.

Results

A teleseismic P delay study was undertaken in the Coso geothermal area, California. 137 events were recorded by 41 seismic stations (1 sec period) in a network approximately 30 km x 50 km with $\sim$ 5 km average station spacing. P wave arrivals were reduced to relative residuals both with respect to the Herrin traveltime tables, and according to least-squares plane wave fit. Relative residuals derived by the two methods are in agreement. The main feature in the relative residual field (Figure 1) is a minor high (relatively greater delay) near Coso Hot Springs (CHS). The amplitude of the high is approximately 0.2 sec. The location of this high residual area is seen to migrate with changes in event azimuth. The center of the high is located 2 to 7 km southeast of CHS for events from the northwest, and 3 to 9 km northwest of CHS for events from the southeast. This suggests a shadow effect. Crude ray tracing places a low velocity body centered 5 to 15 km beneath CHS and Devils Kitchen. Size and velocity contrast for this body could not be uniquely determined by simple ray tracing. Formal inversion of the residual data was made using the linear block inversion method developed by Aki and others. The three-dimensional velocity structure thus modelled is characterized by a deep, broad north-south trending zone of slightly lowered velocity ($\Delta V/V \sim 2$ to 4%; depth 20-30 km) under Sugarloaf Mountain-Devils Kitchen, paralleling the eastern Sierra front. In addition, a small isolated low velocity body ($\Delta V/V \sim 4$ to 8%) is observed directly below Devils Kitchen, from 5 to 15 km depth, not much more than 5 km across. The deep north-south trending feature is probably associated with the Sierra root lying directly to the west, but may also be associated with the rhyoltic volcanic belt lying above it. The location of a body under Devils Kitchen coincides with the center of a heat flow anomaly observed by Combs, a seismic noise high located by Teledyne-Geotech, and recent surface hydrothermal activity.



BEST-FIT PLANE WAVE RELATIVE RESIDUALS - NW EVENTS



BEST-FIT PLANE WAVE RELATIVE RESIDUALS - SE EVENTS

Crustal Inhomogeneity in Seismically Active Areas

8-9930-02231

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Goal

To study the nature of crustal inhomogeneity as it relates to seismicity patterns, or lack thereof, and the application to earthquake prediction. The principal area of study will be that portion of central California in which the USGS seismic telemetry network is operating. Principal source of data will be microearthquake waveforms, and seismicity information, as recorded on and summarized by that network. As a working hypothesis the crust is imagined to be broken into polygonal blocks, on a large scale. Each block may have a fairly uniform velocity structure within it, but this structure may be expected to vary from one block to another. Block boundaries may be expected to be seismically active, but of course not in every case.

Investigations

An extensive review of the literature on application of microearthquake networks to earthquake prediction is underway, in cooperation with Willie Lee. This review is providing me with a broader base from which to research the crustal inhomogeneity problem. It will result in a paper with Willie Lee as senior author.

In this report period a small effort has gone into assisting in getting digitized seismic waveform data from the ECLIPSE seismic data analysis system to the larger Honeywell/MULTICS general purpose computer, for analysis and plotting of waveforms and seismicity as well. Although I had previously selected the DISSPLA graphics package as the primary graphics tool to use on MULTICS, this seems to have changed. The GEOLAB interactive analysis and display system as conceived, developed and installed on MULTICS by Jim Herriot, has recently been augmented by Pete Ward to handle seismic traces on a large scale, very efficiently. Unless something unexpected happens, I plan to use GEOLAB for the analysis and graphics required on this project.

Results

A paper, with Willie Lee as senior author, is taking shape on the application of microearthquake networks to earthquake prediction.

Maintenance and minor changes in the real-time, on-line earthquake detection and location system for the central California seismic network, developed under the now-defunct project "Automatic Earthquake Processing", is continuing.

UNIVERSITY OF SOUTHERN CALIFORNIA

SUMMARY REPORT

U. S. G. S. Grant No. 14-08-0001-G-484

FABRIC, TEXTURAL CHARACTERISTICS, MINERALOGY, AND PETROCHEMISTRY OF INTRAFAULT MATERIAL ALONG THE SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

1 December 1977 to 30 November 1978

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The present trace of the San Andreas fault in southern California traverses an extensive igneous crystalline terrane. The principal cataclastic rock formed at the upper levels of the present trace of the fault is unindurated gouge. However, the nature of this gouge is decidedly different from the "clay gouge" reported by Wu, et al. (1975) for central California. The fault gouge that we have analyzed from two of four sites targeted for this year (Figure 1) is formed from a range of igneous rock types including diorite, tonalite, and granite. The resultant gouge is essentially rock flour representing a milled down equivalent of the original quartz, two feldspar, and minor sphene mineralogy. Biotite, hornblende, and Fe-Ti oxides were totally destroyed and this was at the expense of chlorite, calcite, and hematite. Kaolinite clay development occurs in only a few samples and existing amounts are minimal.

Petrochemically, this form of cataclasis that we have investigated is largely an isochemical process. Some hydration occurs but the maximum amount was less than 2.2% added H_2O. By studying a 375 meter deep core from a tonalite pluton adjacent to the fault, several samples (67% of those analyzed) experienced a depletion in Sr during cataclasis. A lessor number had an enrichment of Ca (result of calcite veining). However, for Si, Al, Ti, Fe, Mg, Mn, K, Na, Li, Rb, and Ba no leaching and/or enrichment occurred.

An intriguing aspect of our work on this drill core is an apparent relation between depth and grain size distribution. Textural analysis indicates that the amount of "clay-size" material is uniformally low with a predominate mode in the fine sand to silt size categories. As shown in Table 1, there is a general decrease in particulate size with depth (and confining pressure) with the predominate mode shifting sequentially from sand to silt size material.

The original fabric of these rocks is commonly not disrupted during the cataclasis. It is evident that the gouge development in these primarily igneous crystalline terranes is an in situ process with minimal mixing of rock types. Fabric analyses reveals that brecciation and shattering, not shearing, is the major mechanism at these upper crustal levels.

Table 1. Summary of Grain Size Distribution from Site 4.

Depth (meters)	Clay[1] (<.0039mm)	Silt (.0039-.0625mm)	Sand (.0625-2.0mm)	Granule (>2.0mm)
213	3.7[2]	24.4	17.2	54.7
214	5.8	22.0	19.8	52.4
260	11.1	15.0	62.1	11.8
331	5.2	36.8	51.7	6.3
362	7.3	40.2	50.2	2.1
368	9.3	40.6	32.4	17.7
373	8.3	57.6	32.9	1.2

[1]Refers to size categories, not mineralogy

[2]Values are in weight percent

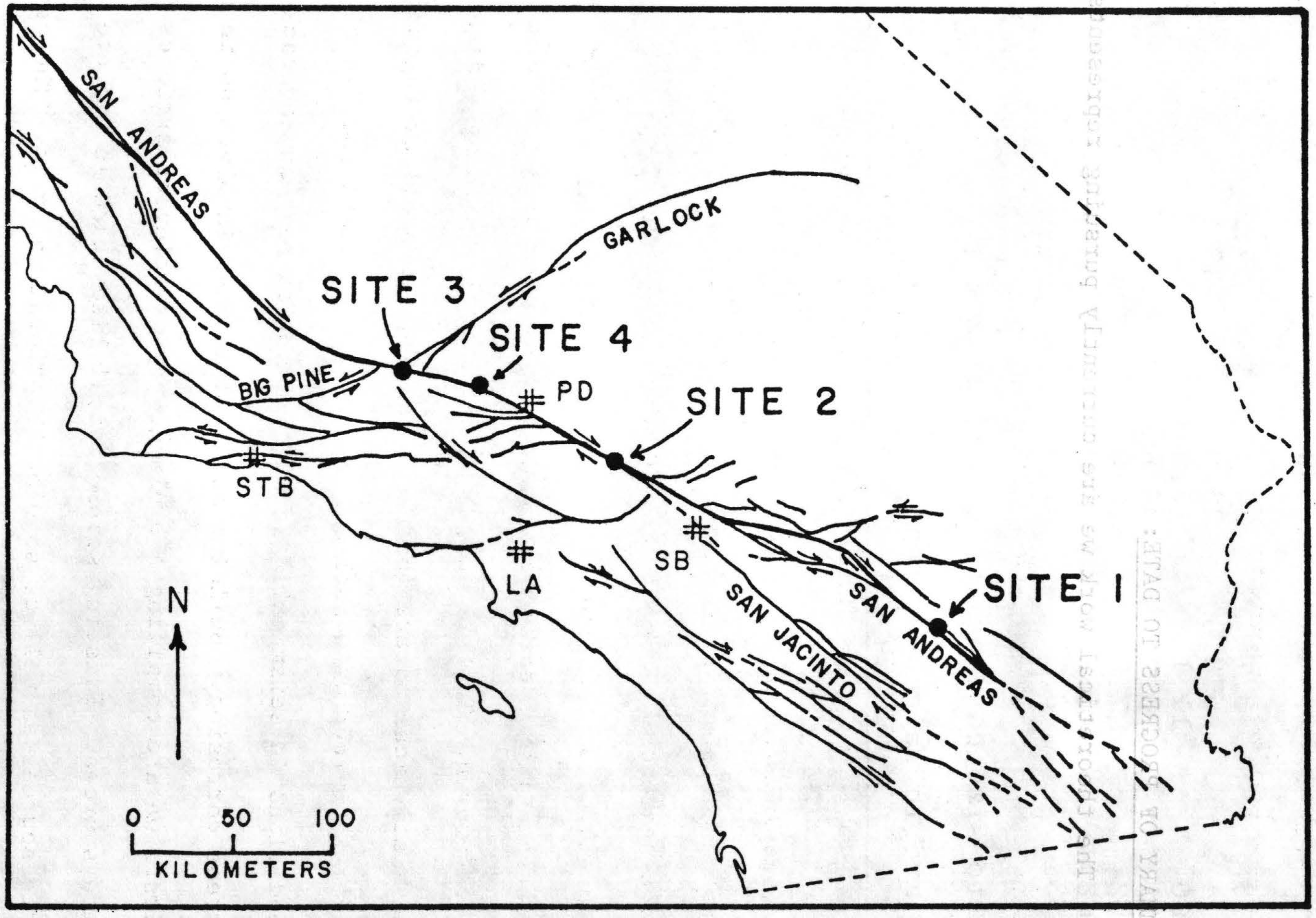

Figure 1. The San Andreas Fault System of Southern California and Sites for Proposed Study.

University of California, Los Angeles
"Stress Corrosion Cracking in Premonitory Earthquake Events," Grant no. USDI-GS 1048-001-16798, Orson L. Anderson, Principal Investigator.

SUMMARY OF PROGRESS TO DATE:

The theoretical work we are currently pursuing represents a logical extension of ideas put forth by Mogi. In a 1966 paper, he states that "...the high degree of similarity between earthquakes and fractures strongly supports the fracture hypothesis of earthquakes." He goes on in his paper to show that fracture theory seems to give a systematic explanation of various individual features of earthquake phenomena such as the mechanism of foreshocks and aftershocks and the mechanism of various patterns of earthquake sequences. More recent sork by Raleigh et al. (1977) and Dunning and Dunn (1978) support this view. However, we hope to develop a more detailed understanding of earthquake phenomena by examining the role of stress corrosion crack growth. To this end, we are currently building a data base concerning the statistical nature (both spatial and temporal) of foreshock and aftershock activity; with such a base, we can evaluate the "in situ" environmental conditions in seismically active areas with respect to crack growth due to stress corrosion. Building such a data base involves us in two operations. First, we are compiling a bibliography of relevant articles which are potential data sources. Existing seismological literature is replete with potential data sources as well as some observational analysis. The series of papers by Utsu (1969, 1970, 1971, 1972) on earthquake statistics is especially useful in this regard. But, second, since it is reasonable to suppose that different source mechanisms for earthquakes may reflect potentially different roles of stress corrosion crack growth in foreshock-aftershock activity, we must be judicious in what we choose from the literature for our data base. On this point, we are still very much in the learning stage. We are trying to separate into distinct groups different types of seismic events so that the statistics of the foreshock-aftershock activity associated with them will be physically appropriate. However, once this data base is established, we can then pursue the connection between our laboratory crack growth observations and the seismological observations of earthquake activity.

In the cantilever crack growth experiment, we are in the preliminary calibrations stages. We have recently finished troubleshooting our vacuum system, so that we now can carefully control the pressure environment in which the crack grows. We presently also are completing the electronics for accurately measuring displacement during crack growth (an important parameter for this crack geometry) and we anticipate conducting calibration tests on our soda-lime glass standards shortly. This work forms the necessary lead-in to conducting experiments on the more physically appropriate silicate specimens.

OJK.

DILATANCY AND MAGNETIC PROPERTIES OF ROCKS UNDER NON-HYDROSTATIC STRESS

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October 30, 1978

Magnetic Susceptibility

A series of laboratory experiments have been initiated to examine the relation between stress, volumetric strain and magnetic susceptibility. Two rocks have been studied in detail, the Ralston intrusive and a gabbro; previous studies on remanent magnetization have been conducted on these same rocks. The experiments were carried out in a beryllium copper pressure vessel at pressures up to 2 kb. The changes in susceptibility were monitored using a bridge apparatus.

The behavior exhibited by both rock types was similar. The result of a typical experiment on the Ralston intrusive with an initial susceptibility of 4.9×10^{-3} emu/cm^3, tested at a confining pressure of 500 bars is shown in Figure 1. The normalized susceptibility and volumetric strain are plotted for the first and second cycle as a function of differential stress. During the first cycle the bulk susceptibility decreased nearly linearly with stress by about 40% up to the point where dilatancy became pronounced. Further loading, with attendent increases in crack porosity, showed a much weaker stress dependence and only an additional 5% or so decrease in susceptibility between 60 and 95% of the fracture strength. Unloading exhibited very little hysteresis in susceptibility and no permanent demagnetization at the completion of the cycle. The loading path for the second cycle was similar to the first. The sample failed at the peak stress with no significant precursory magnetic change.

The behavior of the gabbro as well as the Ralston at higher confining pressure and multiple cycles was essentially the same as shown in Figure 1. The observed characteristics of the response of magnetic susceptibility to stress for these two rocks were:

1. the onset of dilatancy produced a pronounced decrease in the slope of the magnetic susceptibility vs stress curve

2. the maximum decrease in susceptibility at the peak stress for each cycle (i.e. 95% of the fracture stress) was on the order of 50%

3. during unloading the magnetic susceptibility recovered with very little hysteresis

4. at the termination of each cycle there was no permanent demagnetization .

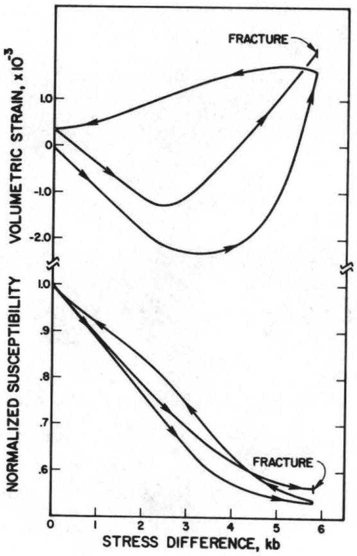

Figure 1

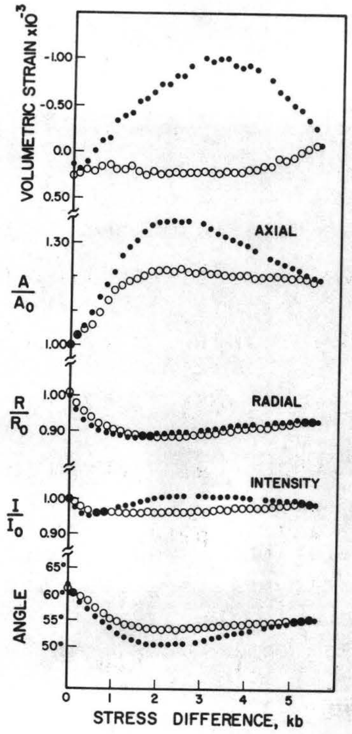

Figure 2

It is of interest to note that the remanent magnetization of these two rocks exhibited markedly different responses to stress. For example the axial component of the magnetic vector (A/A_o) in the Ralston (Figure 2) increased by 30% or so upon loading whereas the axial component of the remanent vector in the gabbro decreased by a similar amount over the same stress range. Therefore it seems that although the effect of stress on remanent magnetization differs markedly and is to some extent dependent on the microstructure of the magnetic grains there is a more uniform effect of stress on magnetic susceptibility.

In terms of earthquake precursory phenomena, the results suggest that there is not a single total magnetic response but rather any observed magnetic change will be strongly dependent on the microstructure of the magnetic mineralogy and the in situ stress level. For example, consider a region with a behavior exhibited by the Ralston intrusive as shown in Figures 1 and 2 for similar samples tested at 500 bars confining pressure where the initial remanent intensity (4.4×10^{-3} emu/cm^3) and initial susceptibility are nearly equal. Compare the change in the axial component of the remanent vector (A/A_o) with the change in magnetic susceptibility which is predominantly the component parallel to the loading axis in our apparatus. In the field very little if any magnetic change would be anticipated if the stresses were insufficient to produce dilatancy because the increase in the axial component of the remanent vector would be cancelled by the decrease in susceptibility. Another region typified by the stress sensitivity of the gabbro, might exhibit a much larger magnetic precursor for the same change in stress. In short the laboratory results can not be universally applied directly to observed precursory phenomena but rather each area must be calibrated through laboratory tests and then correlated with the observed magnetic precursor.

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SOME SPECIFIC EXPERIMENTAL AND FIELD STUDIES PERTAINING DIRECTLY TO THE MECHANISMS OF SEISMIC AND ASEISMIC FAULTING

Summary of final (second semi-annual) technical report for FY 1978 covering the period 1 April 1978 to 30 September 1978.

Principal Investigators: B K.Atkinson, E H Rutter, R H Sibson, S H White.

Contract No: 14-08-0001-G-466

Telephone number: 01-589-5111 X1654

Date: 15 October 1978

Significant progress has been made with all three sub-projects in this study and separate summaries are presented below:

1) Experimental Study of Aseismic Fault Slip

Several long term (up to 6 months) creep and constant strain rate triaxial experiments have been performed on wet, pre-faulted Tennessee Sandstone at 300^0 and 400^0C. Detailed microstructural studies of these deformed specimens and of those deformed in stress relaxation experiments have been completed, mainly by using high voltage transmission electron microscopy. A few preliminary stress relaxation experiments on a pure orthoquartzite (Oughtibridge Gannister) have also been performed. These were conducted on both wet and dry pre-faulted samples.

The new experiments on Tennessee Sandstone, to higher strains than the stress relaxation experiments reported earlier, confirm the dramatic weakening that this rock displays when strain rate is progressively lowered below about $10^{-6}S^{-1}$. The stress/strain rate data derived from creep and constant strain rate experiments are entirely consistent with the data reported earlier from stress relaxation experiments and with the theoretical prediction of a model in which the rate of sliding is controlled by the rate of removal of asperities by pressure solution (eg linear viscous behaviour). This evidence alone, however, cannot be considered as proof of the validity of the model.

The results of microscopy strongly suggest that diffusive mass transfer processes occur in the experiments on wet Tennessee Sandstone. We have observed the recrystallisation of pre-existing deformed illite to an oriented aggregate of smaller new grains, the segregation and growth of mica beards on broken quartz fragments, and the syntectonic formation of quartz overgrowths and new quartz grains.

The pure orthoquartzite data show no influence of the presence of water on strength even at strain rates down to ca $10^{-10}S^{-1}$. This supports the idea that the presence of phyllosilicates in the Tennessee Sandstone may be a factor that exerts a determining influence on strength rather than something which merely accompanies a more fundamental process.

The occurrence of syntectonic quartz overgrowths in the deformed Tennessee Sandstone indicates that pressure solution of quartz may be important in determining deformation rate, although clear microstructural evidence of attrition and/or sliding of neighbouring grains accommodated by diffusive mass transfer has not yet been recognised. The theoretical model would apply equally well, however, if the main precipitating phase were mica, provided that the rate limiting step remains the diffusion of silica species in an aqueous phase which behaves like a solution.

2) Fracture Mechanics Studies of Slow and Fast Cracking in Rocks and Minerals

We report here the results of double torsion and Hertzian indentation studies of slow, stable, tensile cracking (stress corrosion) in synthetic quartz. Studies of crack propagation have been made in air with various humidities at 20^0C and in liquid water at temperatures up to 80^0C. A preliminary study of the influence of pH on crack propagation has also been carried out. In addition, we report the results of double torsion experiments to study stress corrosion of Arkansas Novaculite (a fine-grained quartz rock: grain size ≃10 micrometres, 93% quartz, 7% calcite and opaques) in liquid water at temperatures up to 80^0C.

Mode I (tensile)-type crack propagation of a material undergoing stress corrosion can be described by its crack velocity (v) - stress intensity factor (K) relationship, where $K = \sigma Y \sqrt{a}$ (σ = remote applied stress, Y = a geometrical constant, a = ½ the crack length). All experiments reported here were performed under conditions favouring crack propagation that is believed to be controlled by reaction between the solid and the reactive environment (ie region I of similar curves obtained for glass). Crack velocities from ca 10^{-4} to $10^{-10}ms^{-1}$ were studied. Calculations suggest that for the rate of crack propagation in quartz to be controlled by the transport of reactive species to the crack tip (ie region 2 of curves for glass) then crack velocities as high as 10^{-1} to $10^{-2}ms^{-1}$ must be reached. In quartz cracked on the a plane in a direction normal to the r plane there is some suggestion that a stress corrosion limit may be encountered at crack velocities of ca $10^{-9}S^{-1}$. No such limit was detected for cracking of novaculite even at velocities down to ca $10^{-10}ms^{-1}$.

The humidity of the environment exerts a strong influence on the crack velocity of quartz. Increasing the concentration of OH- ions (ie increasing pH) in the environment increases crack velocities at low values of K.

The experimental data were described by an equation of the form $v = v_o{}' \exp(\Delta H/RT) K^n$, where $V_o{}'$, n are constants, ΔH is the activation enthalpy, R is the gas constant and T is the absolute temperature. A summary of the experimental results are presented in the table below.

Material	Test method	ΔH(kJ mole^{-1})	Stress corrosion index, n
Synthetic Quartz a-plane cracked normal to z	DT	52.5 ± 3.8	12.6 ± 0.6
a-plane cracked normal to r	DT		19.9 ± 1.7
r-plane	H		20.4
Arkansas Novaculite	DT	69.5 ± 1.7	25.1 ± 1.5

NB DT = double torsion, H = Hertzian indentation

Note the structural dependence of the stress corrosion index in quartz.

By a suitable integration of the K-V curve it is possible to predict the dependence of the tensile fracture stress on stress rate or strain rate. For Arkansas Novaculite in liquid water at $20^{0}C$ a 7% reduction in fracture stress is predicted per decade reduction in strain rate due to stress corrosion. At strain rates in the range $10^{-7}S^{-1}$ to $10^{-3}S^{-1}$ there is a fair agreement between the theoretical predictions of tensile strength and experimental determinations that were made using four-point bend specimens.

3) Factors Affecting the Genesis of Fault Rocks

Our programme of sampling fault rocks from the Alpine Fault Zone in New Zealand was completed over the interval 28th July - 3rd September. A technique for the coring and preservation of natural fault gouge without disruption of the internal fabric has been developed. The results of these field studies tend to confirm and extend last year's preliminary conclusions that:

1. The composite NW-SE section we have established across the fault zone, though locally disrupted, gives a passage from cataclasite through augen mylonite to schist-derived mylonite on the upthrown side which probably reflects the original distribution of fault rocks with depth below near-surface gouge zones.

2. Within the fault zone, mylonitic foliation generally dips $40\text{-}50^{0}$SE and there are indications from gravity models for the Southern Alps that this is close to the dip of the fault zone at depth.

3. Penetrative stretching lineations within the mylonites plunge in a direction sub-parallel to the present-day slip vector between the Indo-Australian and Pacific Plates, indicating that the mylonites (and other fault rocks within the Alpine Fault Zone proper) result from the Late Cainozoic phase of compression across the Alpine Fault. Thus even the comparatively high grade biotite-garnet schist-derived mylonites are probably Late Miocene or younger in age.

4. Pseudotachylyte friction-melt is fairly widely distributed along the fault zone; we have tentatively identified it at 20 localities. Though best developed in association with cataclasites, it can be found cutting all other fault rock types apart from gouge. As a consequence of the continuing uplift along the Alpine Fault in post-Miocene times, originally ductile mylonites have apparently been raised to a level where seismic slip along discrete planar fractures (often coincident with the mylonitic foliation) becomes the preferential mode of failure.

5. Survival of moderate to high-grade mylonites without pervasive retrogression during uplift may be attributed to either a general lack of hydrothermal fluids. or shear stress heating within the fault zone, or some combination of these factors.

Further theoretical studies have been carried out in an attempt to relate radiation characteristics to processes occurring on earthquake faults during slip. The composite source parameters, radiant flux (energy radiated per unit area of an earthquake fault in unit time) and radiant flux per unit displacement should reflect the power dissipated on a fault during slip, and thus the seismic efficiency. Values for moderate-to-large earthquakes range over two orders of magnitude, implying considerable variations in efficiency, even for events of similar magnitude occurring on faults of the same type. If high efficiency faulting does occur, it is more likely to arise through a low temperature mechanism involving the transient boosting of fluid pressures on the fault.

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Rock Mechanics

8-9960-01179

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Investigations

1. Laboratory studies of the rheological properties of fault gouge at elevated temperature.

2. Laboratory studies of compaction and dilatancy of fault gouge during shearing.

3. Laboratory studies of creep in fault gouge at constant stress.

4. Laboratory studies of the acoustic emission in rock during creep.

Results

1. A systematic study of the rheological properties of fault gouge has commenced. We have deformed samples of rock containing a saw cut filled with fault gouge at pressures up to 4.5 Kb and temperatures to 400°C. To date the simulated gouge has been either crushed granite or crushed serpentine. The studies are continuing.

2. A cylindrical sample of Westerly Granite 76.2 mm in diameter and 191 mm long, containing a saw-cut oriented at 30 to the axis and filled with crushed granite, was loaded triaxially at a confining pressure of 400 MPa. Changes in pore volume of the simulated fault zone were measured during application of confining pressure and axial loading to failure by sudden stick-slip. Our sample decreased steadily in volume upon application of axial load up to the point at which sliding on the saw-cut stated. At this point, the rate of change of volume decreased until just before failure when a volume increase was recorded. Sudden slip occurred at stress below that required to cause dilatancy in intact rock, suggesting that before eathquakes gouge might show premonitory changes as changing seismic velocity or resistivity that would not appear in intact rock surrounding a fault zone. Experiments in which multiple stick-slip events occur on a single sample are being performed in order to investigate volume changes during shearing of pre-compacted material. One of these experiments suggests that after the gouge layer has been compacted by one stick-slip cycle, further failures are accompanied by compaction during rising stress and dilation before stick-slip failure.

3. The time dependent deformation of Westerly granite specimens containing artificial faults filled with crushed Westerly granite was studied under

conditions of constant differential stress and high confining pressure. Differential stress was controlled at a constant level during fault slip by an on-line computer program which corrected for the decrease in the area of frictional contact and subsequent increase in the true stress across the fault. Fault creep was monitored as the differential stress was increased in steps and then held constant for periods of up to two days. At 400 MPa confining pressure only decaying primary creep occurred below 800 MPa of differential stress. Between 800 and 1000 MPa of differential stress primary creep was followed by constant rate secondary creep, and the slip rate increased with increased differential stress. At approximately 1100 MPa of deifferential stress primary and secondary creep were followed by violent stick-slip. Although both the time to violent slip and the differential stress at which sudden slip occurred varied some what, no tertiary stage of accelerating fault creep longer than the two second minimum data acquisition period of the recording system was recognizable. Our results suggest that, although tertiary fault creep does not appear to be significant at high confining pressure, stress buildup along faults prior to violent slip should be evidenced by an increased rate of fault creep.

4. A cylindrical sample of Westerly Granite was subjected to a constant stress of 50 MPa confining pressure and 50 MPa axial load. For 60 hours prior to failure of the sample, arrival times and amplitudes of acoustic emission events were recorded. Approximately 50,000 microseismic events were located from the arrival time data. These show that, with the onset of tertiary creep, microfracturing changed from a random pattern to a nucleus of intense cracking located on the eventual fracture plane. This result suggests that brittle fracture in granite ocurs as the culmination of an unstable process in which crack growth occurs in a localized region. In addition, P-wave velocity was measured during the experiment at varying angles to the axis of the sample to measure velocity anisotropy. The ratio of slow (traveling perpendicular to the maximum compressive stress) to fast (parallel to maximum compressive stress) P-wave velocity dropped during the experiment from .55 to .45. If such large anisotropies existed in the field, they could prove useful in earthquake prediction in inferring regions of high deviatoric stress.

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TRANSIENT CREEP AND SEMIBRITTLE BEHAVIOR OF ROCKS

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Summary

As part of the research proposed under this contract, Carter and Kirby (1978) have completed a preliminary review of transient creep in metals, ceramics and rocks. Although semibrittle processes were discussed in general as were anelastic, low temperature transient and steady state creep, the review focused on high temperature transient creep. The two important high temperature transient creep flow laws commonly employed are:

$$\varepsilon_t = \varepsilon_T(1 - \exp(-t/t_R)) \tag{1}$$

and

$$\varepsilon_t = \beta t^m = \beta_o \, \sigma^n \, t^m \exp(-E/RT) \tag{2}$$

where ε_T is the total transient creep strain, t_R is a relaxation time, β_o is a constant, σ is the stress and n the stress exponent, t is time and m the time exponent, E is the activation for the rate-controlling process and R and T have their usual significance. Of these, equation (1) is more reasonable physically and fits well the few high temperature, high strain transient creep data available for the test. However the Andrade equation (2) has been applied extensively to most transient creep data for rocks and provides a lower bound on the creep strain to be expected under geologically interesting conditions. It is concluded that appreciable strains can be achieved by transient creep and, for crystalline rocks, such deformation may well dominate throughout the crust.

Carter and Kirby (1978) also concluded that only experimental data obtained at moderate to high confining pressure were meaningful in application to natural deformations because void formation, boundary sliding and microfracturing probably constitute a substantial part of the creep strain in unconfined tests. This conclusion is supported by the observation that activation energies obtained for unconfined tests are much lower than those obtained for confined tests and that the latter are near those observed for steady state creep and those expected for self-diffusion, suggesting similar rate-controlling processes. Recommendations were made: (1) to make an extensive effort to fit existing and new transient creep data to the physically more meaningful equation (1); and (2) attempt to correlate extensive constant strain rate data in the work-hardening regime with

those in the transient creep regime. Finally, it was pointed out that the central problem in assessing the physical meaning of all these low strain data is the lack of information on the deformation processes responsible. It was suggested that, at least under moderate physical conditions, crystalline rocks deform in transient creep dominantly by semibrittle processes.

As a starting point in recognizing semibrittle processes in rocks, we have analyzed some eighty experiments on quartz and quartzite carried out by Heard and Carter (1968) in gas apparatus at 6-10 kb confining pressure, 500° to 1020°C, strain rates from 10^{-3} to 10^{-7}/sec. and strains near 10 percent. Carter and Heard were interested only in ductile flow processes and this new study was aimed at characterizing semibrittle processes. For both Simpson orthoquartzite and for single crystals with basal planes in orientations of maximum shearing stress it was possible to construct rough isotherms separating semibrittle and ductile behavior. As expected, the trends of these isotherms are such that the transition should take place at lower temperatures and lower stresses at geological strain rates. Inasmuch as none of the specimens deformed by purely brittle mechanisms under the conditions employed, brittle-semibrittle boundaries could not be delineated.

Quartz single crystals exhibited two types of semibrittle behavior: (1) sharp faults parallel to the basal plane associated with adjacent zones of undulatory extinction; and (2) wide fault zones either nearly basal or inclined to σ_1 at about 30° and containing intensely deformed and disoriented blocks within the zones. While the former type was more typical of high temperature, low stress deformation, both types occurred together in many of the specimens. That is, it was not possible to establish a given type of behavior with stress level, a topic of concern in the proposed research. It was discovered, however, that the sense of shear along basal faults could be assessed accurately by rotations of the c-axis, due to basal and subbasal mechanisms, adjacent to the zones. This observation could prove to be useful in inferring senses of shear and principal stress orientations in larger faults.

Semibrittle deformational characteristics of polycrystalline quartz are considerably different from those of single crystals, presumably because of constraints provided by surrounding grains. Faults are few, occurring mainly along grain boundaries and commonly terminated when they abut against a grain although occasionally their prolongation may be seen as an intense kink in the grain. The most distinguishing characteristic of semibrittle behavior in these experiments is the presence of thin, irregular zones of intense rotation that seem to have no particular crystallographic or stress control. These irregular kinks commonly emanate from grain boundaries and are believed to be zones of concentrated plastic flow initiated by stress concentrations. A few of these zones are associated with intragranular faults and, if the grains were not constrained, I believe that faulting would ensue from many of them. It would appear, therefore, as if concentrated plastic deformation in these experiments precedes faulting and hence the process is truly semibrittle in nature.

It is evident that this work on quartz merely marks the beginning and will have to be extended further both to experimentally and naturally deformed quartz as well as other silicate crystalline rocks. This effort,as well as our continuing work on analysis of transient creep, provides the focus for research during the remaining tenure of this contract.

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Mechanics of Earthquake Faulting

8-9960-01182

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Investigations

1. Began detailed laboratory analysis of the propagation of unstable slip on a simulated fault in granitic rock.

2. Continued investigation of constitutive relationships for fault slip and the role of adsorbed water in controlling fault friction.

Results

1. Signals from an array of strain gages and displacement transducers adjacent to a simulated fault in a large granite block were recorded over a frequency range of 0-50 kHz. During unstable slip, fault displacements often show sharp onset and simple linear increase with time. In such events the magnitude of the slip velocity correlates with the dynamic stress drop giving $\sim$1 cm/sec slip velocity per 1 bar stress drop. Some events show a more complex character consisting of two or three distinct phases with differing slip velocities. Shear strain adjacent to the fault plotted against fault slip shows a displacement-weakening of friction over a characteristic displacement of 3-6 μM at the onset of instability. This supports previously reported observations indicating that the characteristic displacement is proportional to surface roughness and that the weakening and consequently the potential for instability arise because of time-dependency of friction.

2. Time dependency of rock friction apparently arises because of asperity creep. Preliminary experiments on small quartz and quartzite samples suggest that asperity creep is caused by weakening of the asperities due to adsorbed water. Samples heated to 300° C in a dry Argon atmosphere for >12 hours show greatly reduced time effects and no instability. Exposure of the "dry" samples to atmospheric humidity restores the time-dependence and slip instability.

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Semi-Annual Technical Report Summary

RECRYSTALLIZED GRAINSIZE

IN

DUCTILE FAULT (MYLONITE) ZONES

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This project involves field mapping and sampling of ductile mylonite zones from a variety of tectonic regimes, followed by measurement of the dynamically recrystallized grainsize (mainly of quartz) in the deformed rocks. Shear stresses can be calculated from the recrystallized grainsize (d) using an equation of the form

$$\sigma = Bd^{-p}$$

where B and p are constants that can be estimated from phenomenological arguments, but which are best determined empirically. Two separate determinations are available for quartz (Twiss, 1977; Mercier et al, 1977) and they give almost identical values for p (0.68, 0.71), but somewhat different values for B (5.5, for σ in MPa, d in mm). The difference in calculated stresses of a factor of 2 is small compared uncertainty from other sources.

The field component of the project is nearing completion, with over 500 samples collected from about 30 zones in 6 tectonically distinct settings. Preparation of thin sections of these samples is well under way, and the grainsize measurements have been made on about 50 samples The stresses calculated from these grainsizes are summarised in figure 1, with values from both the above forms of equation (1) included.

We have developed a rapid and accurate method of measuring grainsizes, and expect to complete the measurements from the specimens in hand within the next 2 months.

The limited results obtained so far suggest the following:-

1) Recrystallized grainsize in any one sample is remarkably uniform, irrespective of finite strain variation within the sample, supporting the concept of a steady state grainsize

2) Suites of samples from most zones show good internal consistency although the total range of calculated stresses is approximately one order of magnitude (20 - 200 MPa).

3) The stress values are at the high end of the generally accepted values for crystal flow, although they are consistent with the high stresses indicated for seismogenic faulting by rock mechanics experiments.

4) No regional or tectonic pattern has yet emerged, but there is some evidence that variables such as temperature, and especially water content may alter the form of equation (1), or at least the values of its constants.

5) Where two periods of deformation and recrystallization are recorded, the latter always gives significantly smaller grainsizes, and thus higher stresses.

6) Recrystallized feldspar grainsizes give calculated stresses approximately five times higher than the quartz in the same sample, suggesting that equation (1) may not be applicable to all minerals in its phenomenological form.

The program for the remainder of the project mainly involves grainsize measurement, and more critical assessment of the various stress/grainsize relationships in view of the geological constraints. Two more localities are still to be sampled.

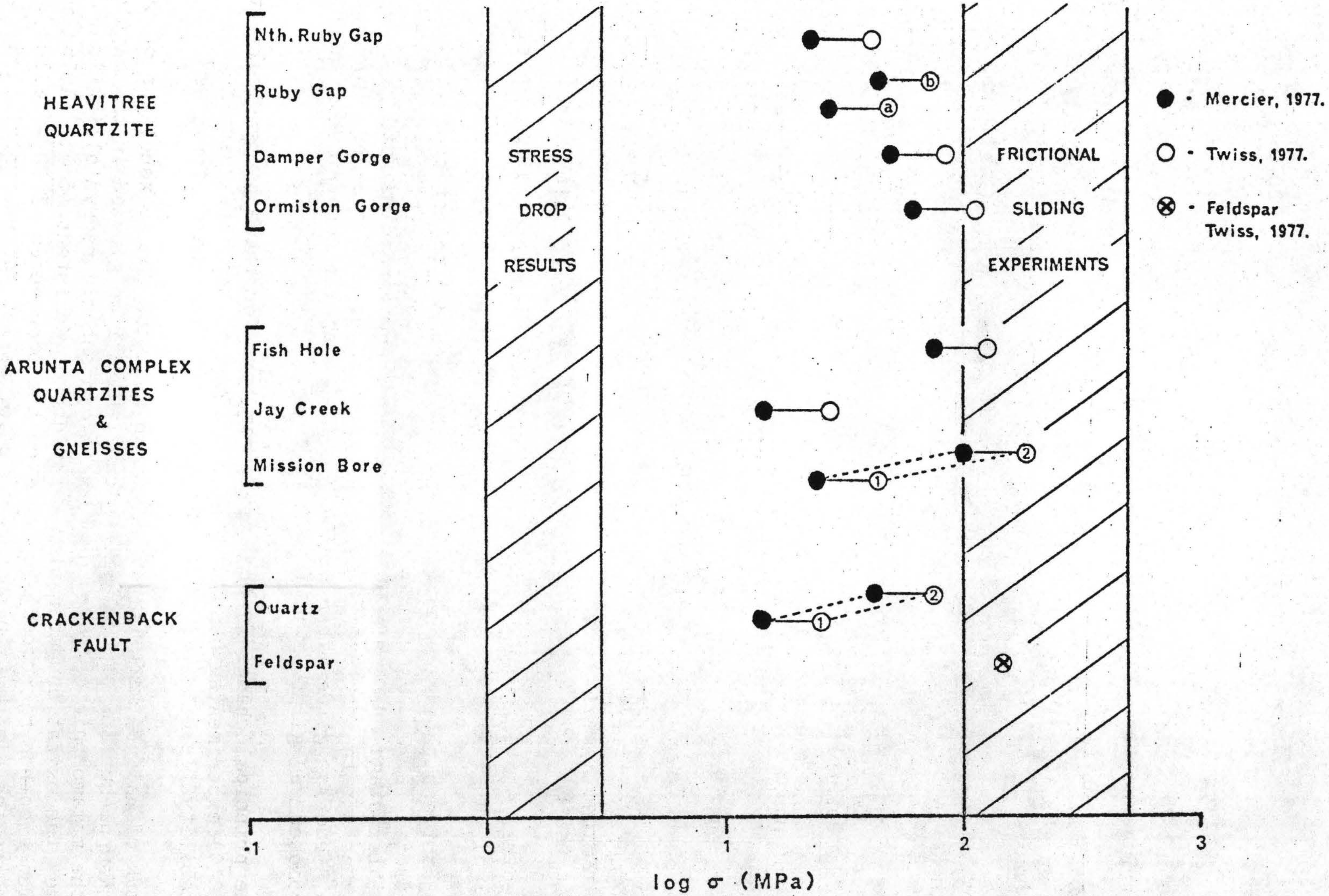

FIGURE 1. Summary of the stress values obtained from the recrystallized grainsizes measured in eight different mylonite zones. Two stress values are given for each recrystallized quartz measurement (joined by solid lines), these correspond to the two different formulae given by Twiss (1977) and Mercier (1977). In rocks which contain two generations of recrystallized quartz grains, dotted lines join the smaller stress values (1) with the larger stress values (2). Two different recrystallized grainsizes were measured in the quartzites from Ruby Gap. The totally recrystallized rocks give stress values (a) and the partially recrystallized rocks give stress values (b).

Experimental Rock Mechanics

8-9960-01180

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Investigations

1. Creep of hydrolytically-weakened synthetic quartz with the objective of isolating the effect of water on the dislocation micromechanics and rheology of silicates.

2. Studies of the dislocation micromechanics and rheology of naturally and experimentally deformed ultramafic rocks.

3. Effects of phase changes on solid state flow in the earth's mantle.

Results

1. As part of his senior thesis, Mark Linker has completed a suite of experiments on samples cut from a synthetic quartz crystal with 365 $OH^-/10^6$ Si atoms and compressed the specimens perpendicular to $(10\bar{1}0)$ at stresses between 80 and 160 MPa and at temperatures from 450 to 750^0C. The results, to be presented at the Fall 1978 AGU meeting, are summarized as follows:

   A. Specimen shortening up to 10% is accomodated by duplex slip on $(01\bar{1}0)$ $\langle a_1 \rangle$ and $(1\bar{1}00)$ $\langle a_3 \rangle$.

   B. In contrast to earlier experiments with specimen orientation which promoted $(2\bar{1}\bar{1}0)$ $\langle c \rangle$ slip, the creep curves showed little, if any, initial stage of accelerating creep rates and hardening rates at higher strain are lower. Absolute creep rates are considerabley lower in these $\langle a \rangle$ glide experiments than in the earlier experiments which promoted $\langle c \rangle$ glide.

   c. The principal change in flow law parameters for these perpendicular to (1010) experiments in going from the alpha to the beta quartz stability field is a lowering of the activation energy for creep.

2. The work of Dale Jackson (1968) has shown that the dunite xenoliths of the 1800-1801 Kaupulehu flow of Hualalai volcano, Hawaii originated in the mantle and that the metamorphic textures are due to syntectonic recrystallization. We have used the oxidation decoration technique of Kohlstedt et al. (1976) and transmission electron microscopy to focus on the occurrence of CO_2- filled bubbles and on the dislocation substructures of relict and recrystallized grains. This work has shown that the textural variations among the dunite tectonite xenoliths are due to progressive deformation and recrystallization of an originally coarse-grained dunite ($\sim$10 mm original apparent grain

diameter). The recrystallized grain size (which averages 0.4 ± 0.2 mm), subgrain size, and free dislocation density do not vary systematically withthe amount of recrystallization, suggesting that the variation in amount of recrystallization are due to variations in the total strain, not in the tectonic shear stress. The tectonic stress inferred from the sizes of subgrains and recrystallized grains and from the free dislocation densities is between 20 and 50 MPa. Many of the free dislocations and dislocation arrays in the relict olivine grains are decorated with CO_2 bubbles, whereas these features are never decorated in the recrystallized grains. We believe that these observations point to the depressurization of the dunites during early deformation, leading to precipitation of free CO_2 from the original grains along dislocations and that subsequent syntectonic recrystallization segregated CO_2 at grain boundaries, leaving the recrystallized grains undecorated by CO_2 bubble precipitates. The couping of depressurization and flow may be accounted for in the simplest way by a diapiric origin for these rocks.

3. In recent years, the effects of the phase changes in the transition zone of the mantle on the rheological properties of the mantle have emerged as a major uncertainty in modelling thermal convection and in understanding the details of the force balance on plates. Direct experiments on the phase transitions are not feasible since controlled deformation experiments at high temperatures are limited by apparatus design to about 20 kilobars pressure. Recent experimental work on this problem has been concentrated on the germanate analogue of forsterite, $Mg_2 GeO_4$, with limited success. Another tack can be taken, that of establishing the effects of the type of phase change on creep properties in non-metallic systems. To this end, we have, in collaboration with Hugh Heard of Lawrence Livermore Laboratory, conducted deformation experiments on cesium chloride, which undergoes a reconstructive phase change at moderate temperatures with a volume change of 15%. Cesium chloride also has an unually high effect of pressure on the temperature of melting. Our preliminary results on the low temperature BCC phase indicates that the large pressure effect on melting temperature is paralleled by a large effect of pressure on flow stress, with strengths nearly doubling on increasing pressure from 50 MPa to 400 MPa. Work continues on refining the flow law in the BCC and in setting up the FCC phase experiments.

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LABORATORY AND FIELD INVESTIGATIONS OF FAULT GOUGE

Grant No. 14-08-0001-G-460

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Frictional Characteristics of Serpentinite from the Motagua Fault Zone in Guatemala

The widespread occurrence of serpentinite along the Motagua fault zone, as well as other major strike-slip, seismogenic faults warrants a systematic investigation to determine how its frictional characteristics may affect slip along the fault. Five locations along the fault zone were sampled to investigate the sliding mode as a function of composition, confining pressure, and displacement rate. Air dried, right circular cylinders, 7.1 cm in length and 3.3 cm in diameter, with a precut 35° to the cylinder and load axes were deformed at confining pressures up to 200 MPa, room temperature, and displacement rates of 10^{-4} cm/sec and 10^{-7} cm/sec. Compositional analyses of the five blocks tested show that the serpentinite can be divided into two groups. One is a mesh-textured serpentinite containing up to 70% serpentine, mostly lizardite, 11% enstatite phenocrysts, 19% oxides, and minor amounts of olivine and carbonate (undifferentiated). The other is a flare-textured serpentinite containing up to 84% serpentine, mostly antigorite, 10% oxides, 6% magnesite and dolomite, and almost no enstatite or olivine. The flare-serpentinite undergoes the transition from stable sliding to stick-slip sliding at confining pressures as low as 10 MPa. The mesh-serpentinite results only in stable sliding up to confining pressures of 200 MPa and a displacement rate of 10^{-4} cm/sec. At a displacement rate of 10^{-7} cm/sec only one of three blocks exhibits stick-slip.

The shear stress required to cause sliding for the stick-slip (flare) blocks is given approximately by $\tau = 0.77\sigma n$, whereas for the stable sliding (mesh) blocks it is given approximately by $\tau = 0.56\sigma n$. This difference may imply that the mechanisms, or interaction of the surface contact areas, differ for both cases. Significant hardness differences between the two groups of serpentinite are indicated by the features observed on the sliding surfaces, such as wear grooves and fracture penetration. The flare-serpentinites are the harder of the two, and it is this relative hardness difference which may be a controlling factor in allowing one group to slide in a stick-slip fashion while the other remains stable.

A model is proposed in which the frictional behavior of serpentinite is responsible for the earthquake generating process. It is based on the concept of patches of difficult slip along the fault plane, created by the presence of serpentinite with a high resistance to frictional sliding. The model is in general agreement with current knowledge of fault creep, rock friction, and the tectonic setting of the Motagua fault zone. If premonitory slip, which has been observed in all stick-slip experiments, can be equated with fault creep it may provide the necessary increment in temperature along the sliding surface to produce (1) high pore pressures due to thermal expansion of the pore fluids, or (2) dehydration of the serpentinte minerals. Both mechanisms may start a sequence of multiple events which will eventually lead to the major earthquake.

Premonitory Slip: Precursive Pore Pressure Changes in Sandstones

Undrained triaxial pore pressure experiments are conducted to determine if pore pressure changes occur during stick-slip of 35° sandstone precuts. Pore pressure changes will reflect possible changes in pore volume (i.e., dilatancy). During the stick portion of the stick-slip cycle, there is a linear increase in the displacement, force, and pore pressure indicating elastic compaction of the specimen. Just prior to the major seismic-slip event, premonitory slip always occurs. Coinciding with the onset of premonitory slip the linear rise in pore pressure and force become nonlinear and level off or decrease immediately prior to the major seismic-slip event. During the major seismic-slip event, the stress on the specimen is relieved resulting in a corresponding coseismic pore pressure drop. The preseismic drop in pore pressure is related to observed microfracture development in grains immediately adjacent to the sliding surface. It is suggested that if dilatancy in the form of increased fracture porosity along the sliding surface is to occur before stick-slip events, premonitory slip is necessary. This is consistent with the model proposed by Dieterich (1978) suggesting the preseismic creep (i.e., premonitory slip) is the underlying process responsible for the observed earthquake precursors attributed to dilatancy.

Simulated Gouge Studies: A Microstructural Investigation of Experimental Shear Zones in Ultrafine-Grained Quartz

Experimental shear zones in ultrafine-grained quartz have been deformed in a triaxial apparatus at 150 MPa confining pressure, 25°C, and a shear strain rate of 10^{-2} sec^{-1}. The microstructural development in the shear zones is studied as a function of total permanent shear strain, using scanning electron microscopy of polished sections of the samples. Riedel shears in the R1 orientation are the main microstructural element present, and it is shown that these form as incipient surfaces during the linear portion of the stress-permanent strain curve. Evidence is presented to suggest that the yield point in the stress-strain curve corresponds to a change in the microscopic character of the Riedel shears from poorly defined zones consisting of interlocking aggregates of small grains to well defined planar surfaces of separation. The fact that the shear surfaces are located within regions of highly comminuted material suggests that the mechanical behavior of the shear zones is controlled by the mechanical behavior of the ultrafine-grained material.

Simulated Gouge Studies: Studies at Elevated Temperatures

Experiments utilizing simulated fault gouge have been conducted at temperatures to 600°C, confining pressures of 150 and 300 MPa, a constant strain rate of 10^{-4} cm sec^{-1}. Room dry specimens, containing simulated gouge of quartz, chlorite and Na-bentonite distributed along a 35° saw in thicknesses of 0.4 and 0.8 mm were deformed. For simulated quartz gouge, the behavior is unaffected by elevated temperatures and stable sliding is characteristic for all tests. Simulated gouges of chlorite were sheared at temperatures to 450°C, and all showed only stable sliding. At 25°C, a yield stress is observed at about 80 MPa shear stress, followed by work hardening. At 300°C, the yield point is higher occurring at about 100 MPa shear stress, and is followed by work hardening behavior. At 450°C, the yield stress is now 110 MPa shear stress and is succeeded by strain softening. Na-bentonite was sheared at temperatures to 450°C. At room temperature, the behavior is one of very low frictional strength and stable sliding. However, as the temperature is raised, the frictional strength increases and a transition to stick-slip occurs between 150° and 300°C. At 450°C, stable sliding is characteristic of this simulated gouge. Current studies are oriented toward mixtures of these simulated gouge materials deformed at elevated temperatures in the presence of fluids.

Baseline Studies of the Feasibility and Reliability of Using Animal Behavior as a Component in the Prediction of Earthquakes.

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In accordance with our 1978 research goals, our investigations have focused on the reliability of reports of abnormal animal behavior in the United States, Central and South America. As a consequence, our briefing volumes, preparatory research and field research have related to these geographic realms.

The approach we have taken provides for intensive post-earthquake surveys which gather both positive and negative reports of unusual precursory behavior and which are of sufficient detail that their reliability and validity can be assessed. The research represents a multi-disciplinary effort which includes two animal behaviorists, who provide the expertise needed to obtain accurately and interpret correctly the information about animal behavior, and a geophysicist, who provides the information needed to understand the geophysical and geological context within which the earthquakes occur. Our subsequent intensive study of three earthquakes have led to a demonstration of the effectiveness of our combined research effort as a methodological approach toward understanding the relationships between animals and earthquakes. On November 22, 1977 an earthquake of magnitude 5.0 occurred near Willits, California, a semi-rural area in which it is customary for households to have some livestock and companion animals. Observations of unusual animal behavior, by people living in the affected area, were studied by a multi-disciplinary team consisting of a geologist, two animal behaviorists and an anthropologist. Over fifty households in the general area of and surrounding the reported epicenter were visited by experienced interviewers who used an interview approach designed to avoid encouraging false reports. The interviews yielded several cases of reports of unusual behavior in at least one of the animals owned by the respondents. The unusual animal behavior reported was not bizarre but was in fact of a form that had been observed in other circumstances. It was defined as unusual because it was inappropriate to the circumstances in which it was manifested. When the positive and negative reports were plotted on a map of the area, there seemed to be a distinct geographic pattern to their distribution. This study demonstrates that in at least one earthquake it has been possible to find very reliable reports of unusual animal behavior prior to an earthquake.

A salient question about the Willits data was whether or not the number of positive reports reflected merely some ambient level of reports of abnormal animal behavior or whether that number might be obtained at the same frequency in the absence of any seismic event. Quite fortuitously we had an opportunity to evaluate this question. On April 23, 1978, an earthquake of 4.9 magnitude, with an estimated depth of 20 kms. occurred near Bata Mountain, Montana. The immediate area around Bata Mountain is uninhabited, but the epicenter is surrounded at a distance by an alluvial valley. This valley transmitted the energy of the earthquake a considerable distance, so that people many miles from the epicenter experienced the shock at intensities comparable to those near the epicenter at Willits. This setting gave us a rural, animal-keeping population which had experienced an earthquake at a considerable distance from a shallow epicenter. Interviews were conducted according to the adopted format used in previous research at Willits, California and in Nueva Concepcion, Guatemala. Thirty reports indicated no unusual animal behavior during the 7 days prior to the main shock. Three positive reports were obtained, only one of which was considered truly valid. Of the remaining two positive reports, one report was deemed not especially credible owing to the low credibility rating assigned to the respondent; the second positive report was considered "shaky" owing to the circumstances surrounding the purported unusual animal behavior. Three additional interviews were conducted during the investigation; however, these interviews revealed that the respondent was not in a position to observe animals, i.e., the respondent either owned no animals or was not around them prior to the earthquake.

The Montana study has effectively served as a control study to which we may usefully compare our other studies. A strong earthquake accompanied by intensities averaging around V (Modified Mercalli scale) was felt by the residents, most of whom are in contact with their pets and domestic animals daily. Thirty out of thirty-six reports yielded no accounts of abnormal animal behavior prior to this earthquake. This data demonstrates that there is not necessarily a high ambient level of reports of abnormal animal behavior at any given time, and 2) reports of abnormal animal behavior do not necessarily accompany seismic events.

In an effort to determine the cross-cultural component in reports of abnormal animal behavior, we chose to investigate a magnitude 5.6 earthquake which occurred at Nueva Concepcion, Guatemala on February 21, 1978. Prior to the earthquake, a culture-specific briefing volume for Guatemala was prepared. This information formed a summary and an analysis of the cultural setting in which a proposed investigation would take place. The interviews conducted at Nueva Concepcion were conducted in a manner identical to that of the previous Willits study. Skilled interpreters native to Guatemala were employed to insure careful and precise understanding of each interview. After transcription of the field tapes the following data was generated: eighteen positive reports of abnormal animal behavior prior to an earthquake, forty-seven negative reports, and one report in which the respondent was not in a position to observe his animals during the 24 hours preceding the earthquake. A map of the area containing points for each interview is included. All negative and positive reports elicited from the study population are believed to be honest and faithful recollections to the best ability of each respondent. Further analysis of this earthquake is pending.

The investigation of earthquakes with selected parameters relating to type of faulting, depth and magnitude is presently emphasized in our project in an effort to clarify whether or not relationships between animal behavior and these paramenters exist. Field research will be conducted using the same methods employed in earlier studies; it is our opinion that this methodology is capable of supplying useful and reliable data for our investigation. Tentative plans exist for future field work in Alaska and Hawaii since the probability of a seismic event occurring there is relatively high.

FUNDAMENTALS OF DEFORMATION AND RUPTURE PROCESSES IN POROUS GEOLOGICAL MATERIALS

14-08-0001-15866 MOD.1

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Summary of Accomplishments

Our studies of deformation and rupture processes have proceeded in four basic areas:

Preferred Planes of Localization

Work by J.R. Rice has been directed to understanding the process of deformation localization into shear zones in the process of fault formation. Previous formulations by Rudnicki and Rice (J. Mech. Phys. Solids, Vol. 23, 1975, pp. 371-394) of the conditions for shear band bifurcations, from previously homogeneous deformation, in frictional, dilatant rock suggest that the surfaces of first localization will differ slightly in orientation from the Mohr-Coulomb rupture direction. The latter direction is that for which the difference between the resolved shear stress and a friction coefficient times the normal stress is maximum, and it is often taken to coincide with the orientation of the final, throughgoing shear rupture. The work provides a possible basis for understanding recently reported (Lindh, Fuis and Mantis, Science, Vol. 201, 1978, pp. 56-58) misorientations between focal plane solutions for foreshocks and for the main earthquake rupture. Similar misorientations between initial surfaces of shear localization and throughgoing ruptures have been reported in fault gouge experiments. For an element of material in pure shear, and assuming a friction coefficient $\mu=0.6$ in the Rudnicki-Rice constitutive relation, the predicted surfaces of first localization are found to vary from 3° to 8° from the Mohr-Coulomb rupture direction for a range of the Rudnicki-Rice dilatancy factor β (ratio of inelastic dilation to inelastic shear increments) from 0 to 0.4. This dilatancy factor range is typical of what is observed in laboratory specimens, and the general range of angular deviation, as well as its sense, seem consistent with the fault plane observations of Lindh et al.

Studies of Frictional Sliding

An adaptable one-dimensional model for sliding in a displacement-controlled, direct shear configuration has been derived by D.A. Simons and applied to study the quasi-static spreading and ultimate instability of bounded slip zones. Hamilton's principle shows that if the approximate displacements in the sliding blocks vary linearly with distance from the interface, but arbitrarily along it, then the slip δ satisfies a forced telegraph equation (a wave equation plus a constant multiple of slip). The coefficients depend explicitly on the thickness, density, and stiffness of the blocks, and the forcing is the excess of the boundary shear over the local frictional resistance. The friction is assumed to drop linearly from the peak strength τ_p at $\delta = 0^+$ to the residual level τ_r when $\delta \geq \delta_c$. A preassigned weakened zone is introduced, with the weakness due either to locally depressed peak strength or to residual stress caused by a lag in the previous slip (seismic gap). Explicit solutions have been obtained for the spread of slip from the weakened zone. As boundary shear increases, instability (defined here as infinite incremental slip or spreading with finite incremental boundary displacement) eventually occurs in all cases, but its nature depends on the relative softening rates of the friction law and the surroundings. For stiff surroundings, instability is delayed until the boundary shear reaches the peak strength τ_p and the slip zone has spread infinitely far. But for soft surroundings, the more representative case for a geophysical setting, instability occurs after finite precursory spreading, and at a level of boundary shear which may only slightly exceed the residual friction level τ_r.

The foregoing study was initiated in part to try to explain some observations of frictional sliding in a gelatin model constructed by an undergraduate in an independent study project under the direction of D.A. Simons.

A. Ruina worked 8 weeks in the summer in the laboratory of Dr. J. Dieterich of U.S.G.S. in Menlo Park. Work there focussed on the development of a small cantilever device that can be used for measurement of sliding displacement across a laboratory fault surface. The device has the advantage that it measures relative displacement locally (thus making unnecessary the subtraction of displacement due to elastic strain) and that it is sensitive to motions with characteristic frequencies as high as 10,000 Hz. The usefulness of the device for dynamic experiments has been indicated by brief trials on Dieterich's large experimental apparatus. The device was also used to check the validity of Dieterich's earlier results on time, velocity, and displacement dependence of friction by measuring force and displacement locally on Dieterich's apparatus.

Ruina has also analyzed a very simple one-dimensional dynamical model where a sliding rock is modeled as a shear beam of finite length extending normal to the interface. The findings show that some results of zero-dimensional (spring-mass) models may be valid in continuous systems as well. That is, concepts such as effective mass and effective stiffness can be used in formulas similar or identical to the "spring-mass" formulas to calculate sliding velocity, distance, and period when friction is modeled by a static and dynamic coefficient.

Inelastic Deformation of Rock

M. Kachanov has continued developing a micromodel for inelastic rock deformation. The model contains two mechanisms of inelasticity: frictional slippage of the original cracks sides relative to each other and secondary crack formation, the latter leading to dilatancy. The contributions of these two mechanisms to an overall deformation depend, for each crack, on the tractions induced on the crack. Since the corresponding three-dimensional crack problem is too difficult for a rigorous solution, the two contributions are approximated by means of some simple but physically reasonable functions. They contain several constants to be specified from experimental data. Typically, uniaxial tests show that axial strain increases almost linearly with stress, whereas lateral strain increases much faster. In triaxial tests with a sufficient lateral pressure the rate of increase of both axial and lateral strains is about the same. These data, obtained from experiments on Westerly granite (Brace, Paulding and Scholtz (1968), Waversik and Brace (1970), Waversik and Fairhurst (1969)), allow specification of the constants. The basic assumption of the model, that dilatancy starts when the "effective" shear traction on the most favorably oriented cracks achieves some critical value, has also been checked by comparison with several sets of experimental data. In each of these sets, data extracted from one experiment were used to predict the threshold of dilatancy in other experiments. Predictions of the model were found to agree satisfactorily with experimental results.

Methods of Determining Hydraulic Diffusivity

V. Li has been conducting a literature survey of field evidence on the fluid transport properties of rocks in or near fault zones. One of the most important yet uncertain parameters which appears in fluid-based precursory models is the hydraulic diffusivity, and it has been carefully reviewed. Two approaches have been taken. The first involves direct measurements such as at drill holes in dam sites. Some in-situ determinations of permeability from flow rates in drill holes have been reexamined using an effective radius of the well rather than the actual radius, to account for the fact that the well intersects joint systems. The second approach taken uses observations of time-dependent fluid diffusion and seismic events. Fluid injection leading to local earthquakes has been studied to determine indirectly the hydraulic diffusivity. Preliminary calculations have been performed, based on the solution for a pressurized spherical cavity in an infinite porous elastic medium, and calibrated with the data of Fletcher and Sykes (JGR 82 3767-3779) for the times at which pumping stopped and at which seismic activity ceased on nearby faults (which had previously slipped due to the reduction of shear strength in the Mohr-Coulomb sense). The calculations indicate that the bulk diffusivity is about 10^4 cm^2/s and the characteristic time ct/r^2 is close to 0.1 (in contrast to unity which is usually taken for granted). Data from geothermal sites show that the variation of permeability follows roughly an exponential decrease with depth, at least for the first 1.5 km.

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3. Nikolaevskii, V., and Rice, J.R., "Current topics on non-elastic deformation of geological materials," in High-Pressure Science and Technology: 6th AIRAPT Conference, Vol. 2: Applications and Mechanical Properties, eds. K.D. Timmerhaus and M.S. Barber, Plenum Press, New York, 1978, pp. 455-464.
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5. Simons, D.A., "The analysis of propagating slip zones in porous elastic media," Proceedings of the AMS-SIAM Symposium on Mathematical Problems in Fracture Mechanics, in press, American Mathematical Society, Providence, 1978; also, Brown University Division of Engineering NSF/USGS Report No. 14, April, 1978.

Summary

Grant Number:	USGS 14-08-0001-G372
Title:	A study of the role of premonitory creep in the mechanism of stick-slip friction in rock
Principal Investigators:	C. H. Scholz and T. L. Johnson
Contractor:	Lamont-Doherty Geological Observatory of Columbia University
Date:	November 1, 1978

Frictional forces were measured during sliding between samples of Barre granite deformed in a servo-controlled triaxial loading machine. Two different responses were observed depending on the type of loading. One, indicating a time dependent increase in friction, has been observed before but the second, paradoxically producing a time-dependent weakening, has not been clearly observed previously. The two effects cannot be separated during steady deformation experiments but can be observed when sliding rate is varied.

Although the fluctuations in force reflecting these competing strength effects are small relative to the total load on the sample, they are sufficient to trigger stick-slip motion. Evidence supporting the concept of a critical displacement (or strain) necessary to establish a new set of asperities is presented. Load fluctuations resulting from the interplay between the two strength effects over the critical distance may determine whether stick-slip or stable sliding will occur. A similar explanation for creep before stick-slip events is strongly supported by the experiments.

Both effects are consistent with a model of surface interaction based on asperities with time dependent strength. In the first case, time-dependent weakening under normal load leads to an increase in real area of asperity contact which reduces the actual stress on the asperities and produces an apparent increase in the nominal strength of the surface when the load on it is increased. The second effect may result from time-dependent failure of asperities under shear stress. Under a fixed displacement boundary condition the movement resulting from asperity failure in shear leads to a reduction in nominal load as the sample relaxes elastically to accommodate movement across the sliding surface. Further experiments studying changes in asperity size and the frictional properties of model individual asperities may enable a quantitative test of the model to be made.

Samples of Barre granite were subjected to a uniaxial stress equal to 87% of their fracture strength for various lengths of time. Crack growth and development as a function of time under load was studied with the scanning electron microscope. New stress-induced cracks appear to be continuously generated. Average crack lengths increased with time as much or more than they did upon loading, but average crack widths remained relatively unchanged, suggesting that cracks close down to an equilibrium value after the sample has been unloaded. Crack interaction with other cavities seemed to increase in time as the numbers of individual cracks increased, until near the onset of tertiary creep crack coalescence may have become more important than the slow growth of individual cracks. The tensile character of stress-induced cracks and other observations by Tapponnier and Brace (1976) were confirmed. There may be a difference in the mode of crack development between tests at constant stress and tests at constant strain rate. Differences in inelastic strain and acoustic emission generated in the two test types also suggest this.

Scanning electron microscope observations of stress-induced crack growth, causing crack-crack and crack-pore interactions within individual grains of Barre granite, show that photoelastic models of cracks are essentially correct and applicable to rock. The stress placed externally on a sample of rock is not the same stress, in magnitude or direction, experienced by cracks within individual grains. Observations of crack-crack and crack-pore interactions can be used to infer the local and regional stress directions, with some ambiguity. Two basic types of microcrack linking, termed *en echelon* and *en passant* are delineated. The former is often a result of relatively large shear stress concentrations between the crack tips in the array. The latter is a combined result of the interaction of the stress fields around two approaching crack tips and the regionally applied stress. Except for some *en echelon* linking, almost all crack growth within grains is an extensional phenomenon.

Publications

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Kranz, R. L., 1979, Crack-crack and crack-pore interactions in stressed granite, Int. J. Rock Mech. Min. Sci., in press.

Rock Physics

8-9960-01181

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Goals

Measurement of compressional and shear wave velocities in crustal rocks as functions of temperature, pressure, fluid pressure, rock type, fabric, density. Development of systematic relations between elasticity and other geophysically or geologically observable quantities (e.g., density, bulk chemistry). Application of results to determination of lithology, fluid pressure, and stress in crustal rocks of tectonically active areas, including fault zones.

Investigations

1. Investigation of systematic relations between wave velocity and other physical properties of Franciscan rocks.

2. Investigation of shear and compressional velocity in saturated basement rocks from Oroville, California area.

3) Investigation of geological structure, lithology, and elasticity of young rocks near the San Andreas fault.

Results

1. Development has continued for a 2 kb pressure vessel designed to allow simultaneous measurements of P and S velocity in saturated and dry rocks with up to 2 kb pore fluid pressure. A weak high-permeability sleeve has been designed, which encloses the rock sample inside an impermeable jacket. The permeable sleeve communicates to the outside of the vessel so pressure in the pore fluid can be maintained at a known value.

2. The apparatus discussed above has been used to measure compressional and shear velocity in a Franciscan metagraywacke that was previously found to be typical in terms of mineralogy, density, and compressional wave velocity at high pressure. Measurements were made to 2 kb confining pressure in the dry rock and in the saturated rock with pore pressure equal to confining pressure. It was found that an effective stress law obtained; that is, when effective stress is small wave velocity in the saturated rock increases with confining pressure at a rate typical of a dry rock at very high pressure. The ratio of compressional to shear wave velocity in this rock does not increase upon saturation as much as it commonly does in crystalline rocks of comparable porosity.

3. Record sections have been made for several events that were recorded east of the San Andreas fault, near Bear Valley, in 1974. Preliminary examination of these data show that simple plane-layer seismic models are inadequate to account for major features of the observations. More complicated velocity models, designed to be consistent with geologic structure and distribution of rock types, are currently being considered.

4) Collection and petrographic analysis of rock samples from the Oroville, California, area has been completed. Samples typical of the major rock types of the area will be used to determine characteristic P and S-wave velocities under dry and saturated conditons. Preliminary work has shown good agreement between low-pressure laboratory measurements in metatuff and average near-surface seismic velocities. In addition, anomalously high velocities found during refraction experiments at Oroville are consistent with velocities measured in the laboratory for a rock taken from a flow within the dominantly metatuff terrane.

Reports

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Stewart, R., 1978, Physical rock properties of a geothermal system: laboratory measurements (abs.), proceedings of workshop on active and passive seismic methods applied to Geothermal Systems, Center for Energy Studies, Univervisty of Texas at Dallas.

Experimental Source Mechanics

8-9960-02113

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Goals

A laboratory fault model has been constructed by James Dieterich. The model consists of a square slab of granite (ca. 2m x 2m x .5m), loaded on its edges. A sawn, polished surface passes through the sample. Application of stress to the edges of the sample results in slip over the polished surface. Static and dynamic strain changes caused by loading and slip will be recorded, allowing measurement of rupture velocity, radiation pattern, stress drop, strain spectra, and seismic efficiency. The data recorded will be used to determine details of fault propagation and to test theoretical predictions. Broad-band measurements of strain changes associated with faulting under well-controlled conditions will be used to gain a better understanding of fault propagation, the sensitivity of fault parameters (e.g., radiation pattern, rutpure velocity, seismic efficiency) to premonitory stress changes, and the transition from premonitory stable sliding to stick-slip. Theoretical models may be tested and, if successful, applied to field observations.

Results

1. Work on this project in the last 6 months has been limited to construction of equipment (strain gage bridges, transducer holders, etc.) to be used in the experiments. Slow delivery of amplifiers for strain gage bridges has prevented any experiments. Other major items (tape recorder components, fast digitizer) necessary for the experiments have been procured.

AN EXPERIMENTAL STUDY OF THE RHEOLOGY OF CRUSTAL ROCKS

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October 15, 1978

The purpose of this study is to gain a more fundamental understanding of the deformation of crustal rocks by determining the grain-scale deformation mechanisms operative at different pressures, temperatures, strain rates, differential stresses, and fluid pressures; to determine both the macroscopic and the microscopic brittle-ductile transitions for these rocks as a function of these variables; and to develop an understanding of the rheology of the polyphase aggregates in terms of the flow properties of their principal constituents, which will allow extrapolation of natural conditions. Our approach is to deform samples of crustal rocks such as granites and diabase in the laboratory at controlled conditions, and to do detailed petrographic and transmission electron microscope (TEM) analysis of the deformed samples. We have completed a study of the deformation mechanisms and brittle-ductile transition as a function of temperature and pressure for dry Westerly granite (Tullis and Yund, 1977). During this past year, we have largely completed a study of hydrolytic weakening in experimentally deformed granites, quartzites, and feldspars rocks (Tullis and Yund, 1978); we have continued to work on the flow properties of quartzite, feldspar rock, and other aplites and fine-grained granites in an effort to understand the flow properties of polyphase aggregates (Tullis and Shelton, in press); we have determined the brittle-ductile transition and its relation to the transition in grain-scale deformation mechanisms for dry Maryland diabase as a function of temperature and pressure; and we have made significant progress in determining the flow properties of clinopyroxenite, orthopyroxenite, and anorthosite, and relating these to the flow properties of the diabase (Kirby and Kronenberg, 1978; Kronenberg and Shelton, 1978; Shelton and Kronenberg, 1978). Our results are summarized below.

Hydrolytic Weakening

Water is known to produce both mechanical and chemical weakening effects in minerals and rocks deformed over a wide range of conditions. We have previously reported on hydrolytic weakening observed in samples of Westerly granite and Hale albite deformed wet; we find that the temperature for the onset of significant dislocation glide and climb is lower for the wet samples than it is for equivalent dry samples. This means that water enhances dislocation glide and climb more than it does microcracking. However, the deformation in the wet samples is much more inhomogeneous than it is in the dry samples, on both the optical and the TEM scales. It appears that cracking and minor faulting occur early in the deformation, probably due to the reduced effective confining pressure, but this is followed by diffusion of water into the crystal structure from the cracks and the grain boundaries, and in these regions hydrolytic weakening occurs, with extensive dislocation glide and even dynamic recrystallization. Thus one sees optical scale fractures which cut either one grain or the entire sample, with little or no offset, and with true recrystallized grains rather than fault gouge along them.

Evidence regarding the role of pressure in hydrolytic weakening is provided by our nominally dry experiments on Westerly granite, Vermont aplite, Hale albite, and Heavitree quartzite, when one considers their yield strength as a function of temperature and pressure, at a given strain rate. The general tendency is for the strength to be strongly pressure dependent at lower temperatures where the dominant deformation mechanism is microcracking, but for this pressure dependence to decrease with increasing temperature as a greater fraction of the deformation is accomplished by dislocation glide and climb. We have noted this tendency for our samples deformed at pressures from 5 to 15 kb; there is a diminished but still significant pressure dependence at 700°C for the granite, the aplite, and the feldspar rock. However, at 900°C, these materials and quartzites all show an inversion of the pressure effect: samples deformed at 15 kb are significantly weaker than those deformed at lower pressures. This may be due to a pressure dependence of hydrolytic weakening. It is likely that the solubility of water in the crystal structure increases with pressure. The data of Yund and Anderson (1978) showing that the diffusivity of 'oxygen' in feldspar increases with increasing fluid pressure from 1000 bars to 4 kb may well be due to an increasing concentration of water in the structure. Griggs (1967) showed that the critical weakening temperature for synthetic quartz depended on the water content; it takes a higher temperature to weaken a crystal with lower water content. Therefore, it may be that 900°C is above the critical weakening temperature for quartz and feldspar for the amount of water which is driven into the crystal structure (from the grain boundaries) by 15 kb confining pressure, but it is below the critical weakening temperature for the amount of water driven into the structure by 5 kb confining pressure. There is another factor which may be of importance; it may be that the chemical activity of water increases with pressure, so that whatever small amount of water is already present in the crystal structure is more active in promoting hydrolytic weakening at higher confining pressures. At present we do not have a sufficient data to evaluate this possibility.

Deformation Mechanisms and Brittle-Ductile Transition for Diabase

The Maryland diabase consists of roughly 50% plagioclase and 50% clinopyroxene. At 5 kb samples develop a through-going fault, and most of the deformation takes place by slip on this fault. At 10 kb deformation proceeds by distributed microcracking and dislocation glide. At 15 kb, the deformation mechanisms change with increasing temperature. Plagioclase shows optical evidence of microcracking at 600°C, but at higher temperatures it shows undulatory extinction. TEM observations show dislocation glide on many systems, mechanical twinning on (010) and (001), and (010) microfracturing. At lower temperatures the plagioclase develops a cellular structure with high densities of tangled dislocations. Dislocation densities remain extremely high up to 800°C, and the deformation is markedly inhomogeneous. Above 800°C increasing amounts of recovery are evidenced by lower dislocation densities and the initiation of dynamic recrystallization.

Also at 15 kb, clinopyroxene grains show optical evidence of microcracking up to 900° C. Undulatory extinction is seen in some pyroxene grains, but it is never as severe as that seen in plagioclase grains in the same sample. TEM observations show that below 800°C, the clinopyroxene deforms by(100),(001) slip and by mechanical twinning on (100) and (001). Above 800°C the deformation occurs by a number of slip systems, and mechanical twinning is less frequent.

In summary, TEM observations indicate that for plagioclase several deformation mechanisms are operative in the temperature interval of 600° to 1000°C, and although there is a continuous increase in the amount of recovery with increasing temperature, there are no abrupt changes in deformation mechanism. In clinopyroxene, however, there is a transition from predominantly (100) mechanical twinning to multiple slip which occurs at about 800°C.

Flow of Polyphase Aggregates

Our goal is to understand the deformation of both granites and diabases in terms of the flow properties of their principal constituents. Thus we have undertaken deformation studies of a polycrystalline albite rock and a quartzite, for comparison with the Westerly granite, and we have also been studying the deformation of a fine-grained aplite with a different ratio of the principal phases than the Westerly granite. We have also been studying the deformation of clinopyroxenite, orthopyroxenite, and anorthosite for comparison with the diabase results.

We find that at low temperatures (600°C) quartzite is stronger than albite rock, and this is in accord with our observations from the deformed granite and aplite samples: at low temperatures where both phases deform predominantly by microcracking, the quartz grains remain essentially undeformed while the feldspar grains are extensively cracked and "flow" around them. However, at higher temperatures (900°C) quartzite is weaker than albite rock, again in accord with our observations from the deformed granite and aplite samples: at these temperatures the quartz grains show more recovery and recrystallization and a more homogeneous deformation than do the feldspar grains. This is an indication that quartz and feldspar have quite different flow laws.

Since feldspar makes up more than half of most "granites", it comes closest to forming the stress-supporting framework, and we would expect the strength and flow properties of the granites to be closest to those of the feldspar. At low temperatures, however, the granite is weaker than a pure feldspar rock, perhaps because of the mica in the granite, which is itself a very weak mineral, and is known to promote crack formation in adjacent phases. At high temperatures the granite appears to have the same strength as the pure feldspar rock, whereas the quartzite is slightly weaker.

We have found that over a broad range of conditions, clinopyroxenite is much stronger than anorthosite. This is in accord with optical and TEM observations which show that in the deformed diabase samples, the plagioclase grains appear to be more ductile and to have undergone greater amounts of strain than the pyroxene grains. The clinopyroxene grains within the deformed diabase contain fewer mechanical twins and lower dislocation densities compared to clinopyroxenite samples deformed at the same conditions to the same sample strains, again indicating that plagioclase has been responsible for most of the diabase deformation.

In general the strength of a polyphase aggregate should correspond to the differential stress supported by its weakest interconnected component. Although the diabase consists of roughly equal proportions of its two components, the plagioclase laths tend to form an interconnected framework, whereas the pyroxene grains tend to be discontinuous and isolated. Thus as a first approximation we would expect the strength of the diabase to be closer to that of anorthosite than that of clinopyroxenite. In fact at 900°C the diabase is significantly weaker than the clinopyroxenite but somewhat stronger than the anorthosite. This difference is probably due to the faster effective strain rate for the plagioclase grains in the diabase.

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Elastic Modulus, Electrical Conductivity, and Fluid Permeability in Rock

by

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June 1978

Summary

I have been studying the elastic behavior and transport properties of rock in which cracks are assumed to be rough surfaces in contact. I developed an equation showing how elastic compressibility should vary with pressure. This equation agrees well with data for three rocks - Casco granite, Westerly granite, and Navajo sandstone - chosen at random. I derived general equations giving effective fluid permeability and electrical resistance in terms of separation between the surfaces and a statistical parameter describing the distribution of asperity heights. I will evaluate these expressions using the statistical parameter from the study of elastic compressibility.

JBWalsh

Joseph B. Walsh
Project Supervisor
Contract No. 14-08-0001-16760

A STUDY OF THE ROLE OF GOUGE IN THE MECHANICS OF FAULTING

Grant # 14-08-16802

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SUMMARY

During the first six months of this study, we have (1) determine precisely the clay mineral content of gouge samples from many fault zones; these are useful as guidelines in making simulated gouge samples for experiments, (2) made detailed obervations and collected samples in fault zones in deep mines of Idaho and along San Andreas fault in California; the fault zones are found to be highly heterogeneous, with severely deformed rocks as well as a substantial amount of clayey gouge; one large outcrop of well-developed gouge was found in granitic rock in the Lake Elizabeth area of Southern California- in contrast to some observations that gouges are rare in the "bend" of the San Andreas zone,(3) studied equilibrium assemblages under high temperatures and found that many expandable clays can exist under pressures and temperatures appropriate for mid-crustal conditions, (4) started experiments on deformation of whole clay samples under 3kb, undrained conditions; the strength of montmorillonite is as low as 0.7 kb.

We are continuing our field sampling program in fault crossing tunnels. These data will be used in providing clues as to how the materials deform in faults. Further assessment of the equilibrium phases of clays under high temperatures will be made. Mechanical experiments on clays consolidated under various conditions and under elevated temperatures will be conducted.

Digital Signal Processing of Seismic Data

8-9930-02101

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Results

Cienega Road Seimicity Patterns

On January 15, 1973, a magnitude 4.1 earthquake occurred on the Cienega Road section of the San Andreas fault zone about 20 km south of the town of Hollister, California. The pattern of seismic activity preceding this earthquake closely resembles the pattern of seismicity preceding large earthquakes that were described by Helleher and Savino. the southeast two-thirds of the 5 km long aftershock zone was aseismic for the 3 months preceding the event. Seismic activity during this 3 month span was confined to the northwest edge of the aseismic zone, in the vicinity of the main shock, and to the southeast edge of the aftershock zone; seismic activity transfer back and forth across the aseismic zone yet no events occur within it.

The magnitude 4.1 main event apparently did not rupture the southeast half of the aseismic zone. Aftershock activity expanded with time, primarily toward the southeast, so that by mid-February, 1973 aftershocks had occurred throughout the aseismic zone that existed prior to the main shock.

Comparisons of Parkfield Earthquakes

The sequences of earthquakes that occurred on the San Andreas fault zone in central California near Parkfield in 1934 and in 1966 are similar in many respects. Each was characterized by an M_L = 5.0 to 5.1 aftershock. The 1934 sequence included and M_L = 5.0 earlier foreshock (64 hours before). Besides the 1934 and 1966 sequence events, isolated M_L = 5.0 Parkfield earthquakes occurred on 28 December 1939 and 16 November 1956. Epicenters for these M_L 5.0 to 5.1 foreshocks, aftershocks, and isolated earthquakes lies within a few kilometers of one another and the epicenters of the 1934 and 1966 sequence mainshocks. Available Wood-Anderson seismograms recorded at Tinemaha (TIN, 240 km, 56^o), Cottonwood (CWC, 220 km, 74^o), Haiwee (HAI, 230 km, 83^o), Santa Barbara (SBC, 180 km, 158^o), Palo Alto, (PAC, 25 km, 317^o), Berkeley (BERK/BKS, 264 km, 325^o), and Nount Hamilton, (MHC, 185 km, 327^o) have been examined for P-waveform differences. For stations recording both the 1934 and 1966 sequences (MHC, BRK, TIN, and SBC) waveforms of the immediate foreshocks are virtually identical, as are those of the two mainshocks. The direction of rupture expansion was to the southeast for the mainshocks and to the northwest for the immediate forshocks.

Reports

Bakun, W. H., and McEvilly, T. V., 1978, Comparisons of Parkfield earthquakes (1934 through 1966), (abs.): EOS, American Geophysical Union Transactions, in press.

Spectral and Time Domain Analysis

8-9930-02105

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Invesigations

Comparisons between data pertinent to source mechanism studies taken from time domain displacement traces of the 0350 GMT August 6, 1975 Oroville aftershock and displacement spectra of the same event leave little doubt that if the S-wave has a relatively simple shape the time domain measurements allow a more precise determination of source radius and stress drop (Fletcher, Brady, and Hanks; in press). Processing the ráw accelerograms for this event to achieve the corrected acceleration, velocity, and displacement traces showed that a careful selection of the filter values used in the high-pass filtering (to eliminate long period error) can markedly reduce distortions present in some of the traces that were evident in a first pass at the processing of the Oroville accelerograms. For the 0350 aftershock, however, of the 10 accelerograms (10 stations - 3 components each) the records from the 3 stations still appeared to be at least partially contaminated by errors in the filter. These records appear to be more strongly affected by near-surface resonances. Work has now been completed on installing a butterworth-type filter in the computer program that computes the corrected acceleration, velocity ahd displacement; and several runs have been made using different roll-off rates and corner frequencies. The butterworth filter appears to offer a significant improvement over the Ormsby filter previously used particularly for the small amplitude records that were seriously contaminated by long period error. The butterworth, however, is also limited in its ability to filter out the very long periods and attempts to move the filter corner to near the reciprocial of 1/2 the record length caused errors in the butterworth response as well. Thus a key to achieving a record with a broad response at the long periods is an adequate length in the digitized record. We are now proceeding to process the rest of the Oroville records with the phase II program modified to accept the butterworth filter, carefully selecting the filter values for every event.

Results

The Lancer digital tape recorder was deployed by John Coakley near the Bishop earthquake (Owens Valley). About 100 earthquakes were recovered during about 3 days of active recording. Rex Allen's trigger algorithim was used to initiate recording to tape when an earthquake occurred. The average S-P time is about 1.8 seconds, and the arrivals do not appear as pulse-like as at

Oroville. Spectra calculated for two of the events (magnitudes $\approx$ 1 and 2.5) again give P corner frequencies substantially higher than the S corner frequencies. For the smaller event the P-wave corner was at 30 Hz and for the S wave at about 10 Hz. The spectra were not corrected for the effect of attenuation. High roll-off rates (w^{-4} or greater) were observed for those spectra. The roll-off rates and signal character (reflecting a high degree of scattering) are more similar to recent records from the Geysers geothermal area than Oroville.

Reports

Fletcher, J. P., A. G. Brady, and T. C. Hanks, Strong motion accelerograms of the Oroville, California aftershocks: Data processing and the aftershock of the 0350 August 6, 1975. Submitted to the BSSA, 1978.

Seismicity and Tectonics

8-9920-01206

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Investigations

1. Peru Seismicity. Earthquakes have been relocated in and surrounding the zone of the 1974 (M_S=7.8) Peru earthquake for the time period 1964-1978. This relocation effort utilizes the joint hypocenter method of relative hypocenter location. Such use of a single location technique creates a homogeneous data base that includes earthquakes located with local or with teleseismic data. The relocated seismicity data are being used to test unusual spatial and space-time seismicity patterns, apparent in inhomogeneous data sets, for seismicity before and following this earthquake.

2. Rio Grande Rift. Teleseismic P-wave delays have been obtained for a 24-element trans-Rio Grande Rift seismometer array that measures about 250 km parallel to the Rift axis by 160 km wide. The seismic sources are 22 teleseismic earthquakes of $M_S \geq 6.0$ occurring during 1977. These P-wave delay data are being inverted to obtain estimates of P-wave velocity anomalies of the crust and upper mantle beneath and adjacent to the Rio Grande Rift.

3. 1957 Aleutian Arc Earthquake. Arrival time and first-motion data are being collected for the Aleutian Arc earthquake of March 9, 1957 (M_S=8.3) and its aftershock series. The relocated earthquakes, coupled with focal mechanism studies of the main shock and larger aftershocks, should provide information leading to tectonic interpretations of this great earthquake and its aftershocks.

4. 1975 Solomon Islands Earthquake. Basic data for relocation of the July 20, 1975 (M_S=7.8) Solomon Islands earthquake and its aftershock series have been collected. Also, many new first-motion and magnitude data have been obtained. The primary goals of this study are to accurately define the aftershock area, precisely determine basic parameters for the main shock, such as moment and displacement, and make a tectonic interpretation of this island arc earthquake and its aftershock sequence.

Results

1. Peru Seismicity. The spatial distribution and space-time patterns of seismicity before and after the 1974 Peru earthquake, as reported in the previous semi-annual report, have been confirmed by a major relocation effort. In general, the relocated epicenters are systematically shifted 5-10 km to the northeast. This systematic epicentral shift occurred both for earthquakes located using teleseismic P-wave arrival time data and for aftershocks

located using local network P- and S-wave arrival times. A large number of new pP and Nana S-wave data were read from WWNSS film chips and these new data have provided greatly increased depth control.

2. Rio Grande Rift. The P-wave delays were determined relative to arrival times at a reference station located approximately 70 km east of the axis of the Rift. These delays, for stations more interior to the Rift than this reference station, are generally positive, but smaller than 0.6 second. However, negative delays of about -0.8 are observed at Lubbock, Texas, which is located in the Great Plains Province, about 400 km east of the reference station. One interpretation of these data is that nearly +1.4 seconds must be accounted for by low-velocity crust and upper mantle material associated with the Rio Grande Rift and that a major lateral change in velocity occurs at depth between the reference station and Lubbock, Texas. A ray-tracing inversion computer program is now being used on the delays for stations interior to the Rift. Preliminary results suggest a greatest large-scale P-wave velocity heterogeneity at a depth of about 120 km. Pronounced small-scale velocity anomalies are evidenced by large, repeatable variations in P-wave delays from various sources. However, these small-scale anomalies are too small to be modeled with the present inversion program.

Reports

Spence, William, 1979, Relative Epicenter Determination Using P-wave Arrival Time Differences, Bull. Seis. Soc. Am. (in press).

Spence, William and Jaksha, Lawrence H., 1978, Teleseismic P-wave Delays Across the Rio Grande Rift (abstract), Proceedings 1978 International Symposium (on) Rift Zones of the Earth: Tectonics and Magmatism of the Rio Grande Rift, Santa Fe, N. Mex. (in press).

Digital Network Operations

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Investigations

The Albuquerque Seismological Laboratory continued to provide technical and operational support to the SRO/ASRO/HGLP observatories, which includes operating supplies, replacement parts, repair service, redesign of equipment, training and on-site maintenance, recalibration and installation. Maintenance is performed at locations as required but also each station is scheduled a visit by a technician every few months for preventive maintenance and training purposes.

During this period USGS personnel met with various individuals and groups in Erlangen, Ankara, Kabul, Tehran, Delhi, Karachi, Quetta, Calcutta, Shillong, Bogota, Bangui, and Paris to discuss the SRO/ASRO programs and station installations.

SRO installations were completed at Shillong, Ankara, and Grafenberg. Agreements were concluded for the installation of SRO stations at the remaining two sites, Bangui and Quetta, and site preparation is underway. Station personnel from Bangui (2) and Wellington are attending an SRO training session at ASL September 18 - October 20. This completes the formal training phase of the SRO/ASRO programs but on-site training will continue as technicians and GS personnel visit the stations.

With the installation of Ankara, Unitech fulfilled their contract responsibilities. There still remains several cost factors in the contract which are under dispute and have to be negotiated before the contract can be completely closed out.

The ASRO network was completed with the modification of the Kongsberg, Norway station in July. The HGLP/ASRO network is now in its final configuration consisting of four HGLP stations and five ASRO stations.

The only item lacking to complete the assembly and testing of the prototype DWWSSN system is the seismic amplifier assembly which will be delivered in October. System operating software has been written and tested. The event detector software has been written and is undergoing evaluation. No significant difficulties have been experienced in the development of the prototype system. However, there have been disheartening delays in contracting for hardware to be used in the production systems, to the extent that the assembly of the 15 systems cannot begin before March 1979. Letters of offer have been withheld pending clarification of fiscal year 1979 funding.

Results

The network provides improved geographical coverage with highly sensitive short and long period seismic sensors with analog and digital magnetic tape recordings.

Goals

The last two SRO stations will be installed. Bangui is tentatively scheduled for installation in January; a schedule for Quetta is less definite because of a series of site preparation approvals that must be obtained from the Pakistan government. With installation nearing completion, more attention will be focused on the evaluation of potential improvements to the SRO and ASRO systems, such as software modifications to improve event detection. The fifteen DWWSSN systems will be assembled, shipped, and installed as funding permits. Site preparation is not required, so significant problems and delays during the installation of these systems are not anticipated. The Albuquerque Lab will continue to provide close technical support to the network stations, including periodic and emergency on-site maintenance by contract technicians.

World-Wide Standardized Seismograph Network (WWSSN)

8-9920-01201

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Investigations

The Albuquerque Seismological Laboratory continued to provide technical and operation support to the WWSSN observatories as funding and staffing permitted.

During this period, 194 WWSSN modules were repaired at ASL, and 270 separate shipments were made to support the network. Fifty-seven stations were supplied with annual shipments of photographic materials and emergency shipments were made to eight stations.

WWSSN observatories at Kabul (KBL), Kongsberg (KON), Antofagasta (ANT), Mashhad (MHI), Peldehue (PEL), Tabriz (TAB), Shiraz (SHI), Sombrero (SOM), Caracas (CAR), Missoula (MSO), Bogota (BOG), Dugway (DUG), Galapagos (GIE), Golden (GOL), Nana (NNA), Albuquerque (ALQ), and La Paz (LPB) were maintained and recalibrated.

Results

A continual flow of high quality seismic data from this network of 115 observatories for use by the seismological community.

W.B.

USGS and Cooperative Observatories

8-9920-01261

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Investigations

Field activities consist of occasional visits to the seismic stations for the purpose of maintenance, calibration, or installation of new instrumentation. Stations are provided with advice on operation, maintenance, and calibration. Also all stations are provided with spare parts, operational supplies, and replacement modules.

Results

These observatories contribute essential data to the NEIS both routinely and on a rapid basis when required. The locations were selected to fill gaps in station locations and to provide better coverage for local events. All data are available for other seismologists when required.

U.S. Seismic Network

9-9920-01899

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Investigations and Results:

Data from the U.S. Seismic Network is recorded continuously in real time at the NEIS office in Golden, Colorado. Currently, 63 channels of SPZ are being recorded at Golden.

Two recent significant changes to the U.S. Seismic Network are as follows:

> CPO, Cumberland Plateau, Tennessee was replaced by ORT, Oak Ridge, Tennessee. Operation of CPO was discontinued because the violent electrical storms in the area made it very difficult to keep the station in operation in an unmanned mode.
>
> The second significant change was the replacement of LD1, LASA Array, Montana with LD3 which is now operated by the U.S. Seismic Network. The U.S. Air Force terminated operation of the LASA Array, July 1, 1978. Arrangements were made to keep one element of the array in operation and transmit the signal direct to Golden over existing Long Lines of the U.S. Seismic Network.

Work is continuing on the development of an event detector using a PDP 11/03 microcomputer. At the present time, 9 channels of data are being monitored experimentally by the 11/03 with a PDP 11/40 used as an interim output device. The 11/40 is obligated to other projects during the normal workday so experimental operation of the event detector has been restricted to the off hours. Funding limitations may preclude development of an operational system in FY '79.

Goals

The goals of the U.S. Seismic Network are to upgrade the quantity and quality of the data received to make possible a more rapid and accurate location of U.S. earthquakes and significant earthquakes worldwide.

W.B.

Tsunami Network Support

8-9920-01263

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Investigations

1. Design, develop, and test microprocessor and microcomputer based TSUNAMI related seismic and tide systems.

2. Design, develop, and test GOES SATELLITE related Tsunami data transmission instrumentation.

Results

1. A microprocessor based Tsunami related seismic system has been developed. This new seismic system is identified as Model TS-4. This TS-4 system is designed to an on-line seismic first arrival detector recorder. It has the capacity to store 15 separate "P" picks. The TS-4 system can be used in conjuction with the GOES satellite system for remote interrogation of TS-4 stations. In addition, these TS-4 stations can operate as non-satellite remote stations. When the TS-4 system is connected to a GOES satellite transceiver, it processes the MLS satellite time code for automatic time upgrading. In the event of satellite MLS time code failure or non-satellite operation, the TS-4 automatically switches to its own secondary time system.

Each "P" pick of the TS-4 system is actually four first arrival picks. The TS-4 has three narrow band filter sections centered at 1.59 Hz, 1.41 Hz, and 1.1 Hz. The time of the normal seismic channel first arrival is recorded as well as the time of each of the 1.59 Hz, 1.41 Hz, and 1.1 Hz channel pick if they are present. Using standard WWSSN short period response seismic signals, teleseismic events are generally detected by the 1.1 Hz channel as well as the main seismic channels. More distant local events are normally detected by the 1.59 Hz channel and the main seismic channel. With the additional 1.59 Hz, 1.41 Hz, and 1.1 Hz picks, it is possible to determine the "P" data from the time of the first arrival as well as the type or location of the event.

2. Five TS-4 systems have been built. One TS-4 is installed at Honolulu, Hawaii, and the second is installed at Palmer, Alaska. The remaining three TS-4 systems will be installed in a tripartite array in the western states.

W.B.

Systems Engineering

8-9920-01262

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Investigations

1. Design, develop, and test microprocessor and microcomputer based seismic instrumentation.

2. Design, develop, procure, and test special electronic systems required by the seismic observatories and related seismic systems.

3. Design, implementation, and testing of microprocessor and microcomputer machine language computer programs for seismic instrumentation and seismic data recording systems.

Results

1. The prototype Digital Recording System (DRS), for implementation at selected WWSSN stations, has been completed and is in the process of system checkout and evaluation. This system is a dual microprocessor controlled seismic digital recording system capable of continually recording three long period seismic channels, event recording three wide-band seismic channels and one to three channels of short period data. The analog seismic data will be converted into digital data by a 16-bit analog-to-digital converter. The digital data will be recorded on a 9-track magnetic recorder in a format similar to the SRO data format of 1000 word records.

2. A Digital Time Encoder (DTE) unit has been developed under contract to replace the mechanical time programmer for the WWSSN system. In addition to being a pin-for-pin replacement unit and providing time marks for the WWSSN photo records, the DTE will also provide parallel digital time signals to the Digital Recording System. These digital time signals will provide the following: year, days of year, hours, minutes, seconds, and millisecond binary coded decimal (BCD) time data.

3. The Digital Recording System software has been completed. The special event detection programs have been incorporated into the recording system software. The software programs are to be programmed into erasable programmable read only memories (EPROMS) as DRS firmware elements.

4. A computer checkout program for testing the Digital Time Encoder was completed and used in the prototype evaluation. This program allowed rapid, flexible test evaluation of this encoder.

W.B.

Albuquerque Observatory

8-9920-01260

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Investigations and Results

The long period seismograph facility at Socorro, New Mexico, has been completed. The cement pads and seismometer tanks are in place. The instrumentation will be installed when scheduling problems are resolved.

The Albuquerque Observatory, along with field teams from the University of Texas at El Paso, the University of Arizona, and New Mexico State University, participated in a refraction experiment across central Arizona. The teams deployed about 40 temporary stations and observed four explosions. These explosions were: (1) a 720 ton detonation of H.E. at a site near Lake Havasu, Arizona, (2) an NTS shot, (3) an 87,000 lb. shot at the Phelps-Dodge copper mine in Morenci, Arizona, and (4) a 110,000 lb. shot at the Cities Service copper mine in Miami, Arizona. A preliminary examination of the field data is encouraging.

Reports

None.

Seismic Observatories

8-9920-01193

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Investigations

Recorded and provisionally interpreted seismological and geomagnetic data at observatories operated at Newport, Washington; Cayey, Puerto Rico, and Guam. At Newport, Washington and Guam, 24-hour standby duty was maintained to provide input to the Tsunami Warning Service operated at Honolulu Observatory by NOAA.

Initiated a cooperative agreement with the Weather Bureau of NOAA under which this Branch has assigned one geophysicist to Adak Observatory (AO) to work with the Weather Bureau employee already assigned there. This step was necessary due to the expanded data gathering role of AO in support of seismological research and the probability of an upgraded WWSSN digital recording system being added to the existing instrumentation. Also under the CIRES program of the University of Colorado a new data collection system will be installed for the processing of Adak data.

Results

Continued to provide data on an immediate basis to the National Earthquake Information Service and the Tsunami Warning Service. Supported the Puerto Rico Project of the Branch of Earthquake Tectonics and Risk. Provided geomagnetic data to the Branch of Electromagnetism and Geomagnetism. Responded to request from the public, interested scientists, state and federal agencies regarding geophysical data and phenomena.

W.C.

Digital Network Data Processing

8-9920-02217

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Investigations and Results

1. The primary effort in this project is the processing of digital magnetic tapes from the global digital recording network. Approximately 225 tapes were edited, checked for quality, corrected when feasible, copied and distributed to data users. Copies of all station tapes are regularly forwarded to SDAC in Alexandria, Virginia, to Patrick AFB, Florida, and to four stations which have a standing order for all of their tapes.

2. Data from all SRO and ASRO stations are also transmitted via the ARPA computer network into a mass storage system called the Datacomputer located in Cambridge, Massachusetts. Research groups with access to the Datacomputer may recall specific time frames of data from any station for analysis.

3. A project has been initiated to construct network-day tapes which would consist of 24 hours of seismic data from each station on the global network for a specific calendar day assembled on one or more magnetic tapes. Approval for the purchase of additional computer equipment has been received, and purchase orders have been placed for most of the hardware. A second PDP 11/34 has been ordered, together with two large disc pack memory storage units. The two 11/34's will be connected through a dual access control system to the disc pack memory units which will allow either processor to access either disc pack unit or allow for both processors to access the same storage unit simultaneously. Data received on tape from the Global Network will be stored on discs and then selectively retrieved in 24 hour segments during the assembly of the day tapes. Software procurement will begin in October 1978. The program is scheduled to be operational in early 1979.

Reports

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Murdock, J. N., and Roller, J. C., 1978, A seismic-refraction experiment performed in the Melones reservoir region of the metamorphic belt, central California (open file).

Murdock, J. N., 1978, Travel time and spectrum stability in the two years preceding the Yellowstone, Wyoming, earthquake of June 30, 1975: Journ. Geophys. Res., vol. 83, no. 134, 1713-1717.

Goals

To provide high quality digital data from all stations in the global network to data users as rapidly as possible. This data is to be in a convenient format written on magnetic tape and accompanied with recent calibration data and all necessary station parameters.

Seismic Review & Data Services

8-9920-01204

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Investigations and Results

The quality control and technical review of 100,000 seismograms (546 station-months) generated by the World-Wide Standardized Seismograph Network (WWSSN) was carried out. Operational standards and seismogram quality of high levels are still being maintained.

Two stations previously reported down due to severe vault flooding are back in operation (Nilore, Pakistan (NIL), and Bulawayo, Rhodesia (BUL)).

Records from the recently installed station at El Paso (EPT) have been received. The gains are 100K and 1500 for the short and long period seismographs respectively with good record quality on these components.

Possible reopening of the Rapid City (RCD), and the Oxford, Mississippi stations is being followed. The Lormes, France (LOR) station may soon be operational but it needs considerable overhauling.

The annual Station Performance Reports for about one-half of the WWSSN stations are in preparation (50 stations). These reports will cover details of instrumental accuracies, timing precision, noise patterns, gain settings, record quality, seismograms received, and any problems that arise pertaining to the station operations and the seismograms generated.

A survey of the microfiche reader-printer field was carried out in view of the film format changeover (70mm chip to 105mm microfiche) soon to be put into effect at the WWSSN Microfilming Service at NOAA/EDS. The results of this study were that present off-the-shelf reader-printers do not meet the special needs of researchers for studying seismograms filmed on the microfiche format. Conversion or modification of the inhouse reader-printers was found to be the best approach.

Advisements and consultations regarding WWSSN matters, other seismograph networks, archiving and/or archived seismic data, World Data Center IDE events and other special events, were carried out with USGS, other government agencies, universities and private parties.

Reports

NA

W.C.

United States Earthquakes

8-9920-01222

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Investigations

Fifty-three earthquakes in 14 states were canvassed for felt and damage data by means of a questionnaire. The questionnaires plus additional data have been evaluated for intensity. The Santa Barbara earthquake of August 13, 1978 was investigated in the field and the damage evaluated. All of the United States earthquake data for 1977 have been either published or in press in the form of quarterly USGS circulars.

Compilation is proceeding on the state lists of earthquakes that are to be used in preparing state seismicity maps.

The catalog of United States seismograph stations has been completed and is being printed. It should be available for distribution by November.

Results

The maximum intensity assigned to an earthquake from April 1 to October 1, 1978 was VII for the August 13, 1978 event located in the Santa Barbara Channel near the coast of California at $34^{\circ}21'$ N., $119^{\circ}42'$ W., origin time 22 54 53.5 UTC, depth 7 km, magnitude 5.1 M_L(PAS), 5.7 M_L(BRK), 5.7 m_b(GS), 5.6 M_S(GS). The Santa Barbara County government estimated that this earthquake caused $12 million in damage, with about half on the University of California, Santa Barbara campus, near Goleta. The quake caused some landslides in the mountains and closed highway 154 temporarily. The worst damage was to the Ward Memorial Blvd. overpass just off U.S. Highway 101. It also caused a freight train derailment of 31 cars of a larger train west of Ellwood.

Intensity VI was assigned to seven earthquakes during this period, six in California and one in Alaska. Most of the reported damage was from cracked plaster or wallboard and hairline cracks in exterior walls.

The list of earthquakes for New Hampshire, Vermont, Massachusetts, Connecticut, Indiana, Florida, Mississippi, Alabama, and Georgia have been completed and preliminary plots of the map have been made.

Reports

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