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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

RESOLVING THE TECTONIC FRAMEWORK OF THE SAN FRANCISCO BAY AREA, CALIFORNIA

A Report of the April 18-20, 1994 Workshop

By

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Summary

Since the M7 1989 Loma Prieta earthquake, which caused significant loss of life and damage as far away as San Francisco and Oakland, a number of studies have been conducted to investigate the structural framework of the San Francisco Bay area. These studies are designed to better evaluate the seismic hazards posed by M7 earthquakes which are forecast for the San Francisco Bay area with 2 to 1 odds in the next 30 years. Judging it was time to discuss the results of these studies, the Coordinating Organization for Northern California Earthquake Research and Technology (CONCERT), with support from the National Science Foundation (NSF) and the U.S. Geological Survey (USGS), held a workshop to review, synthesize, and integrate a wide-range of earth science data and models. Topics reviewed at the workshop included: (1) deep-crustal seismic reflection/refraction studies, (2) geological investigations and digital geographic information systems (GIS), (3) higher-resolution studies of fault geometry and fault slip rates based on seismic sounding, coring, and trenching, (4) seismicity studies, (5) geodetic studies of plate motions, (6) potential field studies, (7) seismic tomography investigations of crustal and upper mantle structure, (8) heat-flow studies, (9) well-log databases, (10) plate reconstructions, and (11) thermal-mechanical models.

Three main priorities for future research emerged from the discussions. First, there was consensus that additional work is needed to understand the geometry of the boundary between the North American and Pacific plates in the San Francisco Bay area. Second, there was widespread agreement that the seismic hazards posed by blind thrusts in the Bay area need to be better evaluated and quantified. **To better evaluate the earthquake hazard posed by blind thrusts there is a high-priority to develop a map showing all the active folds in the Bay area.** Third, there was interest in determining whether there are any disagreements between fault slip rates derived from geologic criteria and those obtained by repeated geodetic measurements.

Finally, there was consensus that a great deal of digital earth science data exist for the San Francisco Bay area and that a catalog of digital data sets should be established. This database will first be established as an on-line catalog of digital data and an on-line list of published bibliographic citations. The goals of making each database accessible are to speed transmission of new results and to foster more rapid reanalysis of existing data.

Introduction

From April 18-20, 1994 the Coordinating Organization for Northern California Earthquake Research and Technology (CONCERT), in cooperation with the National Science Foundation (NSF) and the U.S. Geological Survey (USGS), sponsored a workshop at the USGS in Menlo Park on "The Structural Framework of the San Francisco Bay area and its Implications for Earthquake Hazards". More than 125 earth science professionals *(see Appendix A)* participated in 2 1/2 days of discussions on the state of knowledge and the unsolved problems regarding the structures of the Bay area, and on priorities to be addressed by future structural framework studies.

Consistent with the objectives of CONCERT *(see Appendix B)*, the workshop sought to integrate results from a diverse suite of earth science studies related to the broad structural framework of the greater San Francisco Bay area. An overall framework for the meeting was provided by an attempt to address the types of information necessary for regional tectonic models, whether to understand the effect of crustal structure on wave propagation and strong ground motion or to better understand the effect of fault slip along one fault segment to the net stresses on nearby fault segments. Almost 2 days were set aside for short presentations by earth science investigators to insure that all participants were aware of planned, ongoing, or recently concluded work *(see outline of agenda in Appendix C).*

Following these brief presentations, three important problems in the San Francisco Bay area were identified for discussion by focus groups. These included: (1) the geometry of the boundary between the North American and Pacific plates, (2) the evaluation and quantification of the seismic hazards posed by blind thrust faults, and (3) the apparent disagreements between fault slip rates derived from geologic criteria and those obtained by repeated geodetic measurements. These problems are discussed in more detail in the following sections.

Finally, the workshop participants discussed means of identifying and sharing existing digital databases containing information needed to define the structural framework of the San Francisco Bay area. Several participants completed database worksheets which sought to identify those who have digital databases they are willing to share *(see Appendix D).* Plans to make a catalog of existing digital data accessible to all interested researchers are discussed in the last section of this report.

Geometry of the Pacific-North American Plate Boundary

A number of unresolved questions about the geometry of this plate boundary and the distribution of strain in the crust and mantle in three-dimensions remain despite the invaluable information provided by the existing earth science data. Deep-crustal seismic data have defined the depth to the base of the crust locally, but the geometry of the base of the crust is still inadequately

known in three-dimensions. Similarly, deep-crustal seismic data have identified slabs interpreted as oceanic crust beneath the continental shelf, but the eastward extents of these slabs are still uncertain. In particular, it is uncertain whether they pass under the San Andreas fault, truncating the fault at depth. The internal structure of the lower crust is still poorly known, allowing a number of possible interpretations. One model, based on the interpretation of potential field (pseudo-gravity) data, is that the magnetic basement rocks beneath the Great Valley underlie the Franciscan rocks as far west as the Hayward and Calaveras faults.

The geometry of the major strike-slip faults, particularly beneath the seismogenic portions of the faults (beneath 14-15 km), is much debated. Three main models have been offered: (1) the faults extend as near-vertical structures throughout the lithosphere, (2) the faults extend nearly vertically to a depth of about 15-20 km, at which depth the strike-slip motion is ramped horizontally eastwards to one master vertical fault which penetrates the lithosphere, and (3) none of the faults are vertical and the motion is taken up solely by low-angle detachments.

Finally, although the subject received little discussion during the general sessions, the role played by fluids in the earthquake cycle, and the structural controls exerted on fluid genesis and migration may be significant.

Approaches to learning more about the Pacific-North America plate boundary include: (1) additional surface geologic studies including improved mapping of the offshore marine geology, (2) integration of multi-disciplinary datasets having differing scales of spatial resolution, (3) improved vertical-incidence seismic reflection images of the middle and lower crust and improved seismic velocity information throughout the crust, (4) improved potential field (gravity and aeromagnetic) and electrical data, (5) obtaining teleseismic and/or broadband receiver function data to determine the lithospheric structure, and (6) additional heat flow measurements to test thermal models.

Evaluation of Earthquake Hazards Posed by Blind Thrusts

Blind thrust faults are those faults which, unlike the major strike slip faults in the Bay area, do not produce faulting of the earth's surface. These faults do, however, produce actively growing folds by their repeated motion. Perhaps the first objective is simply to identify and determine the location of blind thrusts in the San Francisco Bay area. The highest priority for locating these thrusts is to compile an active fold map, because by definition these faults do not produce mappable fault traces. Once identified, these fold structures can be evaluated in more detail, using a variety of methods. These studies would seek to estimate the amount and rate of shortening represented by the fold, leading eventually to slip rates, event histories, earthquake recurrence intervals, and estimates of maximum earthquake magnitudes. Balanced cross sections can be useful tool for estimating the total displacements on the blind thrust faults from the fold geometry. Quantitative geomorphology can be used to estimate uplift rates on

the folds. Seismicity and geophysical profiling can be used to constrain fold and fault geometries.

Important questions that need to be resolved include:

- o What is the best way to characterize blind thrusts and display them on maps? How do we represent the observables on a map? At what point should we as a community be satisfied that enough is known about a structure to deem it an active blind thrust?
- o What is the origin of the blind thrust faulting? Is it an inherent result of the plate motions, a result of the fault geometry, a result of block rotation, or a combination of these?
- o How is the rest of the lithosphere deforming during the growth of the folds? Is it thickening or extending? What is the relationship of the thrust faults to the strike slip faults? What is the regional geometry and sense of slip of the thrust faults?

Geologic versus Geodetic Slip Rates

Geologically and geodetically determined slip rates measured across the entire Pacific-North America plate boundary are in close agreement. Across some individual faults, however, there are significant disagreements that may yield important insight into the earthquake cycle. One view of the apparent local disagreements is that geodetically determined slip rates are based on models and interpretation as well as data, and that locally these assumptions can be incorrect. In addition, geologic estimates of slip rates represent averages over many earthquake cycles whereas the earthquake cycle is much longer than the duration of any existing geodetic measurements.

One important aspect of both geologic and geodetic slip rates is the along strike variation displayed by these data. These spatial variations may provide insight into structural controls on the slip rates.

Need for On-line Digital Databases

It was obvious during the workshop that a great deal of information concerning the structural framework of the San Francisco Bay area already exists. A survey taken before the workshop revealed that there are existing digital databases for several types of geological and geophysical data *(see Appendix D).* Nonetheless, it is difficult to compare and integrate these data unless they have been placed into a common database, and plotted at identical scales. As a first step towards establishing this common database, it was proposed that the completed survey worksheets be placed on-line so that any interested individual could access them to learn how to obtain digital data for their own use.

Similarly, it was deemed important to try to develop an on-line database containing bibliographic citations to the published earth science literature for the

San Francisco Bay area. As a first step towards establishing this bibliographic database, earth scientists are urged to e-mail the reference lists they have used in their own recent papers on the San Francisco Bay area to Tom Brocher (brocher@andreas.wr.usgs.gov). Alternatively, they can mail a diskette with these reference lists to Tom Brocher (USGS, MS 977, 345 Middlefield Rd., Menlo Park, CA 94025). These lists will be collated and then maintained on-line for others to use for their own research purposes.

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APPENDIX B. CONCERT BACKGROUND

CONCERT MISSION STATEMENT

The Coordinating Organization for Northern California Earthquake Research and Technology (*CONCERT*) is dedicated to the reduction of earthquake risk in Northern California. CONCERT fosters basic and applied earthquake-related research conducted by earth scientists, engineers, social scientists, and other interested professionals, and works with the user community to define and maintain a coordinated program to identify earthquake hazards and to reduce earthquake risk. CONCERT facilitates the dissemination and utilization of research results.

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APPENDIX C. WORKSHOP AGENDA

Welcome and Introduction

Bill Bakun (USGS)
- Presented an overview of CONCERT

Overview of Information Needed by Modelers

Kevin Furlong (Pennsylvania State University)
- Discussed need for modeler input into the pre-experiment design of large experiments
- Emphasized that models can provide linkages between databases

Status of Deep-crustal Seismic Reflection/Refraction Studies

Tom Brocher (USGS) - Overview Speaker
- Showed locations of existing deep crustal seismic data in Bay area
- Described how these data can be used to constrain geodynamic models
- Presented an overview of the deep crustal results from Bay area Seismic Imaging eXperiment (BASIX)

Steve Holbrook (Woods Hole Oceanographic Institution)
- Presented an overview of BASIX wide-angle results
- Emphasized uncertainties of the velocity models

John Hole (Stanford University)
- Discussed reflections from the Moho from BASIX
- Described how reflected refractions obtained by BASIX can be used to image the dip of the San Andreas fault

Rufus Catchings (USGS)
- Discussed land-based refraction/wide-angle reflection studies and velocity models along the San Andreas fault
- Proposed that topography on Moho can focus arrivals at large ranges for earthquakes on southern Peninsula

Vince Ramirez (Onesta Corp.)
- Described industry reflection lines from the San Joaquin Valley as an analog to the structures one would expect to find in the Bay area

Jeff Unruh (William Lettis Associates)
- Used industry reflection lines in the Western Sacramento Valley to locate blind thrusts and estimate slip rates

Tom Wright (Chevron, retired)
- Discussed problems with gaining access to industry seismic reflection data
- Described attempts to obtain American Geological Institute (AGI) oversight of data transfer and establishment of a national archive for industry data

Steve Lewis (USGS)
- Announced that 3000 km of marine Gulf-Chevron data in marine sanctuaries offshore central and northern California are now available

Status of Geological Investigations and Geographic Information System (GIS) Databases

Earl Brabb (USGS) - Overview Speaker
- Discussed the status of digital geologic maps in Bay area
- Announced the donation to USGS by industry of large amounts of microfossil data needed to unravel structure in Bay area

Carol Prentice (USGS)
- Announced creation of a group to prepare strip map for San Francisco Peninsula
- This is the only portion of SAF not currently on a USGS strip map

Carl Wentworth (USGS)
- Discussed Geographic Information Systems (GIS)/Bay area Regional Database (BARD) in use at USGS, Menlo Park
- Described digital Bay area maps released in USGS OFR 93-693

Keith Kelson (William Lettis Associates)
- Presented evidence for blind thrusts in Santa Cruz Mtns/Santa Clara Valley
- Posed the issue of how to represent blind thrusts on geologic/hazard maps

Ramon Arrowsmith (Stanford University)
- Discussed geologic and GPS estimates of uplift rates in the Santa Cruz Mtns

Bill Lettis (William Lettis Associates)
- Presented an overview of hazards posed by blind thrusts in the Bay area
- Reviewed geologic slip rates in Bay area

John Wakabayashi (self-employed)
- Presented an overview of coherent patterns in Franciscan basement structure

Russ Graymer (USGS)
- Briefly reviewed the relation of seismicity to geology at southern end of the Calaveras fault

Status of High-Resolution Studies (Seismic sounding, geophysical surveys, coring, trenching)

Dave Schwartz (USGS) - Overview Speaker
- Described 17 sites across strike-slip faults in Bay area that provide fault slip rates
- Presented an overview of the mud faults in S. San Francisco Bay

Mike Marlow (USGS)
- Described mud faults in S. San Francisco Bay that have been detected using high-resolution seismic reflection profiles

Pat Hart (USGS)
- Presented intermediate resolution (1-sec) reflection records obtained during a shake-down cruise last year
- Announced May 1994 experiment planned to use new tool in four regions in the Bay area

Pat Williams (LBL)
- Presented structures in Sacramento Delta imaged by high-resolution seismic reflection profiling
- Described 50- to 100-m-long cores near Pittsburg-Kirby fault tied to seismic profiles

Gary Simpson (William Lettis Associates)
- Reviewed Calaveras trench studies
- Determined a 5 mm/yr slip rate but need better age control
- Noted that the San Gregorio fault is predominately strike slip

Tim Hall (Geomatrix)
- Announced that a trench across the San Andreas Fault on SF Peninsula at Filoli yields a slip rate on SAF of 21 mm/yr ± 4 mm/yr

Jim Lienkaemper (USGS)
- Described work on a Quaternary fault map and database for the SF Bay region which is part of the larger "ILP Project II-2, United States Map of Major Active Faults" headed by Mike Machette (USGS-Denver)

Mike Rymer (USGS)
- Announced plans for a high-resolution seismic reflection profile on ramp of the San Mateo bridge in Foster City across lineations identified from airphotos

Status of Seismicity/Geodetic Studies

Dave Oppenheimer (USGS) - Overview Speaker
- Described joint USGS/UCBerkeley on-line seismicity database with remote login
- Discussed 1:250,000 seismicity maps in GIS format

Mary Lou Zoback (USGS)
- Summarized seismicity along the San Andreas fault
- Described pronounced along strike variations in seismicity along the San Francisco peninsula, with seismicity being located off the fault in the south near Loma Prieta and on the fault near Daly City

Bob Kovach (Stanford University)
- Described project to map faults in vicinity of Stanford University
- Seismicity appears to project to mapped thrusts and uplifts in this vicinity

Lind Gee (UC Berkeley)
- Described the existing and planned Berkeley broad band array of 8 stations

Mike Lisowski (USGS) - Overview Speaker
- Presented overview of geodetic studies in Bay area

Jeff Freymueller (Stanford University)
- Described the GPS geodetics of California north of Bay area

Paul Segall (Stanford University)
- Discussed evidence for thrust faulting from the co-seismic deformation during Loma Prieta

Nancy King (USGS)
- Described plans to use continuous GPS recording to obtain better slip rates

Jon Galehouse (San Francisco State University)
- Discussed long time series of creep rates on faults in Bay area
- Showed that creep rates have changed significantly after Loma Prieta earthquake

Status of Potential Field (Aeromagnetic/Gravity) and Electrical Studies

Bob Jachens (USGS) - Overview Speaker
- Presented an overview of potential field data
- Discussed plans for acquisition of aeromagnetic data this FY

Vic Labson (USGS)
- Presented magnetotelluric models of Loma Prieta
- These models show that the San Andreas fault zone is extremely conductive and isolated from other major faults

Mary Lou Zoback (USGS)
- Discussed potential field data along San Francisco Bay mud faults

Andy Griscom (USGS)
- Discussed an interpretation of pseudo-gravity data in terms of determining the western edge of the Great Valley basement

Carter Roberts (USGS)
- Discussed potential field databases including locations of gravity samples
- Summarized work in filling in gaps in gravity coverage along Calaveras fault

Status of Seismic Tomography Studies

Kevin Furlong (Pennsylvania State University) - Overview Speaker
- Reviewed mantle tomography in northern California
- Presented results of crustal tomography using earthquakes and BASIX data

John Evans (USGS)
- Presented results of a teleseismic residual study of Loma Prieta epicentral region showing anomaly in upper mantle along the fault

Bill Foxall (UC Berkeley)
- Summarized results of a crustal tomography study of Loma Prieta epicentral region showing high velocity (6.9 km/s) blocks

Status of Heat flow Studies in Bay Area

Colin Williams (USGS) - Overview Speaker
- Presented an overview of heat flow in California and the Bay area
- Showed that heat flow on Pacific plate and in Bay Block is identical
- Showed a rapid decrease in heat flow to the east of the Calaveras fault

Status of Well-log Databases

Dave Rogers (Rogers/Pacific) - Overview Speaker
- Reviewed digital database of 4700 expandable well logs (dating to 1880s) for Alameda and Contra Costa counties

Janine Weber Band (UC Berkeley)
- Briefly described plans to develop other well-log databases

Vince Ramirez (Onesta Corporation)
- Commented on availability of oil industry databases

Status of Plate Reconstructions/Thermal Mechanical Models

Bob Simpson (USGS) - Overview Speaker
- Discussed simple elastic modeling of Bay area faults
- Compared predictions in post-seismic stress changes to changes in seismicity and slip rates observed after the Loma Prieta earthquake

Larry Hutchings (LLNL)
- Announced existence and purpose of CONCERT Focus Group on Dynamic Modeling

Wayne Thatcher (USGS)
- Discussed thermo-mechanical models of ductile shear zones in terms of seismic velocity and other geophysical anomalies

Kevin Furlong (Pennsylvania State University)
- Discussed the rheology of crustal and mantle rocks and implications for fault behavior

Ruth Harris (USGS)
- Discussed attempts to model the dynamic rupture at offset fault strands

Chi-Yuen Wang (UC Berkeley)
- Discussed results of elastic-plastic deformation and stress models based on current fault geometry

Joe Andrews (USGS)
- Announced plans for elastic-plastic deformation and stress modeling

Andrei Sarna-Wojcicki (USGS)
- Presented estimates of slip on SAF based on a 6 myo tuff unit found in Bay area and in an offshore fan deposit

Pat McCrory (USGS)
- Discussed Pacific-North America plate reconstructions based on marine magnetic anomalies

Bob Bohannon (USGS)
- Presented Pacific-North America plate reconstructions
- Emphasized evidence that the Pacific and North America plates never converged

Discussion in Working Focus Groups

- Geometry of the plate boundary in three-dimensions (Leader: Steve Holbrook, Woods Hole Oceanographic Institution)
- How to evaluate earthquake hazards posed by blind thrusts (Leader: Bill Lettis, William Lettis Associates)
- Geologic versus geodetic slip rates (Leader: Jeff Freymueller, Stanford University)

Reports from Working Groups/Discussion of Important Unresolved Structural Problems

Open Discussion of Strategy to Develop On-line, Digital Databases

Discussion of Recommendations to CONCERT

APPENDIX D. EXISTING DIGITAL DATABASES

Persons Having Digital Databases

Name	Type of Digital Data
Tom Brocher	Wide-angle deep-crustal seismic data
Pedro de Alba	Soil boring data from Treasure Island
John Evans	Teleseismic travel time residuals
John Hole/Simon Klemperer	Wide-angle deep-crustal seismic data
Bob McLaughlin/Carl Wentworth	Digital geologic maps
David Oppenheimer	Online earthquake locations, first-motion mechanisms, phase data, and waveforms
Carter Roberts/Bob Jachens	Gravity data
Carl Wentworth	Digital geologic materials map
Colin Williams	Subsurface temperatures and heat flow determinations
Ivan Wong	Relocated earthquake hypocenters
M.L. Zoback	Relocated seismicity, digital version of bay mud faults, gridded topography data, stress data, Quaternary faults digitized from new state 1:250,000 map