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# University of California
# Campus Laboratory Collaboration Program

# Advanced Earthquake Hazards Project
# Annual Report, January 31, 1998

Dr. Paul Kasameyer, Dr. William Foxall, Dr. Lawrence Hutchings,
Dr. Shawn Larsen, and Dr. David McCallen
Lawrence Livermore National Laboratory

Prof. Abolhassan Astaneh-Asl, Prof. David Brillinger,
Prof. Thomas McEvilly, and Prof. Barbara Romanowicz
University of California, Berkeley

Prof. David D. Jackson
University of California, Los Angeles

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Lawrence
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# University of California

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## Project Description

The "Advanced Earthquake Hazards" CLC Project has three objectives. First, to carry out research that enhances the physical basis for earthquake hazard prediction in order to improve the estimation of future seismic hazards and the response of structures to them. We address hazard estimation needs spanning technical issues in tectonics, fault mechanics, wave propagation, strong ground-motion prediction, structural response, and risk assessment. Second, to apply this cross-disciplinary analysis to the earthquake response of the western span of the Bay Bridge, which connects San Francisco and Oakland. This bridge is crucial for Northern California and has the highest traffic volume of any bridge in the US ( about 250,000 cars per day). Finally, with colleagues throughout the state, to participate in an effort to develop a proposal to the National Science Foundation for a statewide California Earthquake Center.

We have taken a cross-disciplinary approach to deal with several research needs:

- Understanding nonlinear dynamic behavior of long-span bridges.
- Producing broadband, realistic, strong-motion time histories with accurate spatial coherency and phasing.
- Understanding and predicting the great variations in ground-motion amplitude caused by variations in source rupture mechanics, site and propagation path.
- Improving our fundamental understanding of the physical processes, pre-, post- and co-seismic tectonic strain fields, and probability distributions underlying the earthquake source models used in time-dependent,probabilistic, seismic hazard analysis and in synthesis of ground motion time histories.

This effort couples strong University of California campus and laboratory capabilities in a range of disciplines (structural modeling, high-performance computing, geology, seismology, and data collection and archiving) into a team that will be successful seeking outside research support.

To date, our project has produced technical successes in several disciplines, and we are beginning to combine them to produce significant results:

- We have developed and tested physics-based methods to calculate rock-site ground motion from DC to 25 Hz produced by realistic earthquake source descriptions in complex geology.
- We have developed and tested complex models of the non-linear response of steel suspension bridges and applied them to the Bay Bridge.
- We have installed weak- and strong-motion and near-static deformation instrumentation throughout the Bay Area.
- We have found that near-static displacements from earthquake rupture scenarios on the Hayward Fault can produce significant motion on the western span of the Bay Bridge.
- We have developed and tested models for earthquake occurrence in space and time and have gained important new insights into the mechanics of earthquake sources.
- We have supported two Ph.D. theses and several peer-reviewed technical papers.

In the coming year, we will study the inelastic response of long-span bridges to realistic inputs, and examine the significance of differential input and rupture model uncertainty on the risk of damage for the Bay Bridge. In addition, we will determine how well the studies of recurrence rates and characteristic earthquakes can limit possible rupture models.

## Summary of Activities

We focused our technical efforts on developing physics-based answers to important questions about seismic hazard and risk estimation. We are motivated to increase the physical basis for hazard prediction because standard, experience-based risk predictions have under-predicted the effects of recent large earthquakes, particularly near the causative fault. There have been surprises in source areas (Northridge, Landers), source effects and propagation (Northridge, Loma Prieta, Kobe), site response (Northridge, Loma Prieta), and structural fragility (Northridge, Kobe). Our plan is to use cross-disciplinary collaboration to answer questions such as: What is the significance of using simplified models? How adequate is the experience base for predicting ground motion, recurrence rates and structural models and response? We describe technical progress below.

## Instrumentation of the Bay Area for earthquake hazard estimation

*Seismic instrumentation*

We are part of the Bay Bridges Instrumentation Program, a large effort to install weak and strong motion seismic instruments to record free-field motions beneath large bridges crossing San Francisco Bay. The instruments accomplish three goals: to record frequent, small earthquakes, so that we know the linear site-specific propagation effects from major faults to these important structures; to record the actual input to the structure, should a significant earthquake occur; and to supplement the Hayward Fault Seismic network (HFN). The HFN is designed to collect accurate, frequent earthquakes from the source area of the Hayward Fault (See Appendix A). The instrumentation supported by the CLC was used as leverage to obtain a $300K grant to UCB for data collection and archiving. By incorporating these sensors into the multi-agency Hayward Fault Network project, we are able to use communication and archiving procedures developed by UCB's Northern California Earthquake Data Center (NCEDC).

The instrument packages, designed by UCB, and installed jointly with LLNL, contain a three-component HS-1 seismometer and a three-component Wilcoxon 731 accelerometer. Each Wilcoxon package has a flat response from 0.1 to 100 Hz and records from a $\mu$g to 0.5 g acceleration. They will capture earthquakes from magnitude-one events to those causing damaging strong motion. Sensors are buried 100 feet into bedrock, from 100 to 1000 feet below the Bay. Data are being recorded on 11 instruments and three will come on line soon. Seismic signals from three sites are sent directly to the NCEDC; the others are visited monthly to collect data tapes.

*Deformation Instrumentation*

We have participated in the development of the Bay Area Regional Deformation network (BARD) of permanent Global Positioning System (GPS) receivers. We purchased one receiver and installed it at Mount Hamilton (MHCB) at the southern end of the San Francisco Bay Area, along the Calaveras fault. More importantly, the CLC funding was used as leverage in a successful proposal to purchase 8 additional receivers. Six receivers have been installed at sites of the Berkeley Digital Seismic Network (BDSN), which already has continuous telemetry, making it possible to acquire GPS data continuously and in quasi-real time at UC Berkeley, at no extra cost. In this project, we supported the development of quasi-real time GPS data analysis procedures, in the framework of the UCB REDI program (Rapid Earthquake Data Integration). Our goals are (1) use GPS data as additional constraints on the co-seismic and near-post seismic deformation effects associated with large earthquakes on Bay Area faults, such as the Hayward Fault and (2) monitor possible regional strain pulses.

Development of GPS quasi-real-time analysis procedures is a cutting-edge technology, in that it requires near-real time estimation of satellite orbits for the GPS constellation. Since relatively accurate orbits are known only after 24 hours delay, extrapolation of orbits is necessary. Preliminary results on the last 6 months of data appear very encouraging. The next step is to densify the distribution of BARD stations accessible in near-real time along the Hayward Fault, which is currently thought to be possibly the most hazardous fault in the Bay Area and is a direct threat to the UC Berkeley campus.

## Development of statistical and mechanical models of earthquake sources

*Insights from high-resolution seismic data recorded at Parkfield, CA*

Our research into earthquake source processes is based primarily on statistical and waveform analyses and mechanical modeling of the Parkfield data set, including a large subset of repeating characteristic earthquakes. The objective of this research is to improve the earthquake source models used in probabilistic seismic hazard analysis and strong ground motion synthesis.

We developed a method to test statistical models of novel multidimensional, very general procedure for the assessment of proposed models for marked point processes in time, such as earthquake size-space-time distributions. We applied this procedure to the Parkfield data set as a whole (repeating and non-repeating earthquakes) to test existing models. A new model that incorporates features of both a self-exciting point process and a Markovian stress-release process provides a satisfactory fit to the data. This work was done by UCB.

We completed processing the Parkfield data set using an automated procedure that identifies repeating similar earthquakes, computes high-accuracy relative locations and relative seismic moments for these events, and develops size-space-time statistical descriptions of their behavior. A recent paper illustrates the dramatic improvement in location resolution yielded by the automated processing compared with routine catalog locations, which has enabled us to discern size-space-time systematics that have hitherto been masked by location errors. Fractal analysis of sub-sets of the data shows that earthquake occurrence on this section of the San Andreas Fault is characterized by tight spatial clusters localized on an essentially two-dimensional plane. This, together with the quasi-periodic recurrence of the clusters, is in marked contrast to models of distributed deformation inferred from previous analyses of low-resolution Parkfield hypocenters. This result strongly supports the characteristic earthquake model as opposed to models of self-organized criticality that preclude time-dependent hazard analysis, at least at the fault zone scale. It is also evidence for strong fault heterogeneity, which is important to characterizing sources for ground-motion synthesis.

Exciting and significant new insights into the earthquake source process were obtained using a simple method for estimating source rupture area, slip per event, and stress drop for the repeating earthquakes. This method relies only on a relatively robust assumption of long-term fault slip, and avoids the uncertainties inherent in estimating source parameters from earthquake spectra. The scaling relations among earthquake size and the source parameters resulting from this analysis are fundamentally different from those conventionally used for source modeling. Contrary to the conventional assumption of constant stress drop, we find that stress drop scales inversely with moment, at least up to magnitude 6. The smallest events (~M1) have stress drops approaching the strengths of intact rock. We are working toward incorporating these results into our source model for the Hayward fault. This effort was carried out by UCB and LLNL.

*Insights from the historic earthquake catalog for California*

We explored seismic source models for California, specifically methods to estimate and test the probability of earthquakes as a function of location, time, and magnitude. We examined two families of source models, which can be taken in linear combinations to form a more complete source model. The first family of models is based on geologically mapped faults. We have constructed a model that assigns earthquakes to specific fault segments, estimating magnitudes using regression relationships for the dependence of magnitude on fault length or area. An important ingredient is the uncertainty of the dependence of magnitude on length; because of this uncertainty, the model allows some rare but quite large earthquakes. These dominate the estimated slip rate and thus control the rate of smaller earthquakes. Without allowing for the magnitude uncertainty, we found it impossible to fit the observed slip rate and earthquake frequency simultaneously. The second family includes areally distributed sources with a density proportional to either smoothed seismicity or geodetically measured shear strain rate. We assign a magnitude distribution having the same shape everywhere, so it is easy to fit seismicity and strain rate, but this model does not fit fault slip-rate explicitly.

We have also developed statistical tests for the agreement between an earthquake source model and an earthquake catalog, allowing for sampling errors and errors in estimating earthquake magnitudes. We have applied this testing procedure to various earthquake prediction schemes, including the Parkfield prediction. We conclude that the "official" Parkfield prediction can be rejected at 95% confidence, and that the historic earthquakes at Parkfield can be explained by a random occurrence of earthquakes having a Gutenberg-Richter magnitude distribution statewide. This work is carried out by UCLA.

## Ground motion

*Synthesis from small earthquakes to capture "unknowable" short-scale geologic variations*

We are researching means to predict strong ground motion using empirical Green's functions, or small earthquakes generated at the source of interest and measured at the site of interest. This work is also supported by another CLC project, "Estimation of the Ground Motion Exposure from Large Earthquakes at Four UC Campuses in Southern California," and has been a cooperative effort between UCSB and LLNL, and participants in LLNL student programs. We have just expanded the study to include a Caltrans seismologist who spends 40% time at LLNL applying these concepts to the Bay Bridge.

The method for synthesis at high frequencies (0.5 to 25 Hz) uses the Green's Function representation relationship to integrate "point-source" earthquakes that contain all the information about path and site complexities needed for linear synthesis. The challenge is to determine what kinematic rupture histories result in accurate syntheses of recorded large earthquakes, and what range of rupture processes we could anticipate for future events. We focused on validating our choices of models, studying the range of hazard parameters that might arise for a future earthquake, and using insitu seismic measurements to tell us about near-surface propagation in rock.

Our progress includes validation of our source characterizations by matching earthquake recordings from the Gulf of Corinth, Loma Prieta, and Saugenay (Quebec) earthquakes; estimationing uncertainties by “post-predicting” the seismograms recorded at 25 sites during the large Loma Prieta earthquake, and documenting that source uncertainty provides a strong contribution to hazard uncertainty by applying the method to the Hayward Fault, and faults in Taiwan and Greece. This effort has led to several ancillary cooperative studies, including an up/down hole study of wave propagation in rock and development of an educational software package.

Having recognized that the source uncertainty is key to estimating the hazard due to an anticipated event, we have studied what details of the Loma Prieta earthquake rupture history could have been anticipated before it occurred. In the future, we will focus on defining limits for the source uncertainty.

*Finite-difference wave propagation model for the Bay Area*

Numerical methods are required to calculate ground motion at frequencies lower than 0.5 Hz. Before this project, we used a method with two deficiencies: it is limited to flat-layer models, and it does not calculate the “near-field” terms, which are important close to the source.

LLNL and USGS-funded UCB scientists have coupled a complex geologic model for northern California to a parallelized and computationally efficient 3-D wave propagation code. This code and the LLNL's high performance computers are being used to evaluate both the near-static displacement and wave propagation effects of earthquakes.

The 3-D wave propagation code, which uses the high-performance architecture of the LLNL Meiko CS-2 machine, is very efficient. It runs approximately 100 times faster than the finite element code DYNA, and is being used with complex models consisting of 45 million nodes. Dr. David Wald, of Caltech and the USGS said, in the *Tri-Valley Herald*, that this is " One of the most powerful codes in the world."

The geologic model of the Bay area represents the local near-surface geology averaged over a few kilometers. Deeper and more distant geology is represented in less detail. The model was coupled to the computer code in a volume 175 x 100 x 40 km in size. The high power of the code allows computations from DC to 1 Hz for this model. The models can be driven by complex rupture scenarios. Figure I shows the wave field during two time periods for a bilateral magnitude 7.25 earthquake on the Hayward Fault. Calculations of this type have demonstrated the strong enhancement and long duration of seismic energy in shallow basins, and the variability of the hazard at a particular location with fault rupture history.

By coupling the numerical and empirical syntheses, and using the complex geologic model, we will be able to synthesize realistic seismic records from DC to 25 Hz. We are currently modifying the source description for this code to be consistent with validated kinematic rupture models described above.

## Structural modeling

Long-span suspension and cable-stayed bridges are among the world's largest architecturally pleasing and essential structures. Most were built prior to the development of computer-based analysis procedures, and many are potentially threatened by earthquakes. Analysis of a major suspension bridge is a daunting task, because of the size and complexity of the structure, the possibility of different inputs at different piers, and the existence of nonlinear phenomena such as sudden impact of the suspended deck parts, rocking of the main towers and foundations, and the effects of gravity on the structural equilibrium. LLNL and UCB have collaborated to study these structures.

We have developed a modeling and analysis tool called SUSPNDRS. It solves for the transient response of extended cable-supported bridges by using an efficient global nonlinear solution framework that accommodates both geometric and material non-linearities. The code allows the structure to be represented in detail with a reduced number of degrees of freedom by implementing characteristic element types to represent real structural elements such as trusses, beams or membranes.

This code is being used by engineering students for a number of problems. In addition, we have developed a detailed nonlinear model of the western span of the Bay Bridge that will accept different seismic input at each pier. Because the model of the bridge has a reduced number of degrees of freedom, we can complete a calculation of nonlinear seismic response in 2-3 hours. This will allow us to run many different seismic inputs through the bridge model, and to determine what aspect of the seismic signal is important. We verified the model in the linear regime by comparing frequencies of normal modes measured on the Bay Bridge in the 1930s. Non-linear calculations with this model are discussed below.

The "realistic" models of the western spans of the Bay Bridge were developed using more sophisticated analytical and computational capabilities of the LLNL and engineering modeling expertise of UCB faculty and students. Parallel to this cutting-edge research activity, we have also been working on developing simpler "engineering" models of the western spans of the Bay Bridge. These models use the modeling technologies that are currently used by structural engineers in design offices, such as Caltrans, to conduct dynamic analysis of long-span cable-supported bridges. These simple models will be analyzed using two frequently used structural analysis programs, ABAQUS and SAP2000. The objective of this activity is to be able to conduct a comparative study of advantages and disadvantages of current structural analysis technology, and make recommendations for improvements in modeling and analysis to obtain more reliable dynamic analysis response in design offices. The records obtained from the Bay Bridges Instrumentation Program and the results of research on ground motion, as discussed earlier, will be directly used in the structural analysis research part to conduct dynamic analyses with multi-support excitations and to refine the structural model.

## What we are learning by combining these capabilities

Detailed information about ground motion is required to make accurate, reliable seismic analyses of long-span bridges By combining the techniques described above to examine the input to and response of the Bay Bridge, we are learning about critical ground-motion issues for these structures. We will investigate issues that include long-period, near-fault motions that are not well represented in the existing strong-motion database, and the effects of spatial variation. These studies require close coupling between seismology and engineering; the interactive, multi-disciplinary investigation of these critical issues represents the strength of our project.

Our work to date illustrates the kind of conclusions that we will be able to draw at the end of Phase I of this project. Figure II shows displacement time histories for one example (the bilateral magnitude 7.25 earthquake on the Hayward Fault that generated Figure I). This is the result of a preliminary coupling of the wave propagation studies with the bridge model. These results are preliminary because of significant uncertainties in the best way to characterize the source in the numerical models. Those uncertainties arise from two sources. The first is the need to ensure that a single earthquake is modeled consistently in codes that perform the syntheses in different frequency bands, an issue that we are actively pursuing. The second is more significant; we find that a very broad range of seismograms can be produced by earthquakes of a fixed moment. We will be investigating the extent that constraints from geophysical studies and source characterization studies can limit this range.

These uncertainties influence the amplitude, but not the general character of the response. The figure shows how well the code can calculate the near-static offsets, in this case parallel to the fault, as the Bay Bridge moves to the northwest on the Pacific plate. In addition, it shows that the near-static offset has an associated dynamic pulse that is very strong. At the Bay Bridge site, most Hayward Fault events produce very strong fault-parallel displacement energy near the fundamental frequency of the bridge. This dynamic pulse is not well represented in strong motion recordings, most of which are unreliable for frequencies below 0.2 Hz due to analog recording and short pre-event memory. This fact has two implications: First, the size and frequency of the dynamic pulse depend strongly on gross features of the kinematic rupture model (such as unilateral versus bilateral rupture). Second, it is difficult to find data to validate our source models at these frequencies, so we are unsure about what source parameters give realistic ground motions at these frequencies. As is shown below, the nature of this pulse is very important for the response of long-span bridges. Our future research will focus on ways to constrain the model parameters that influence this part of the signal.

## Improving Interactions

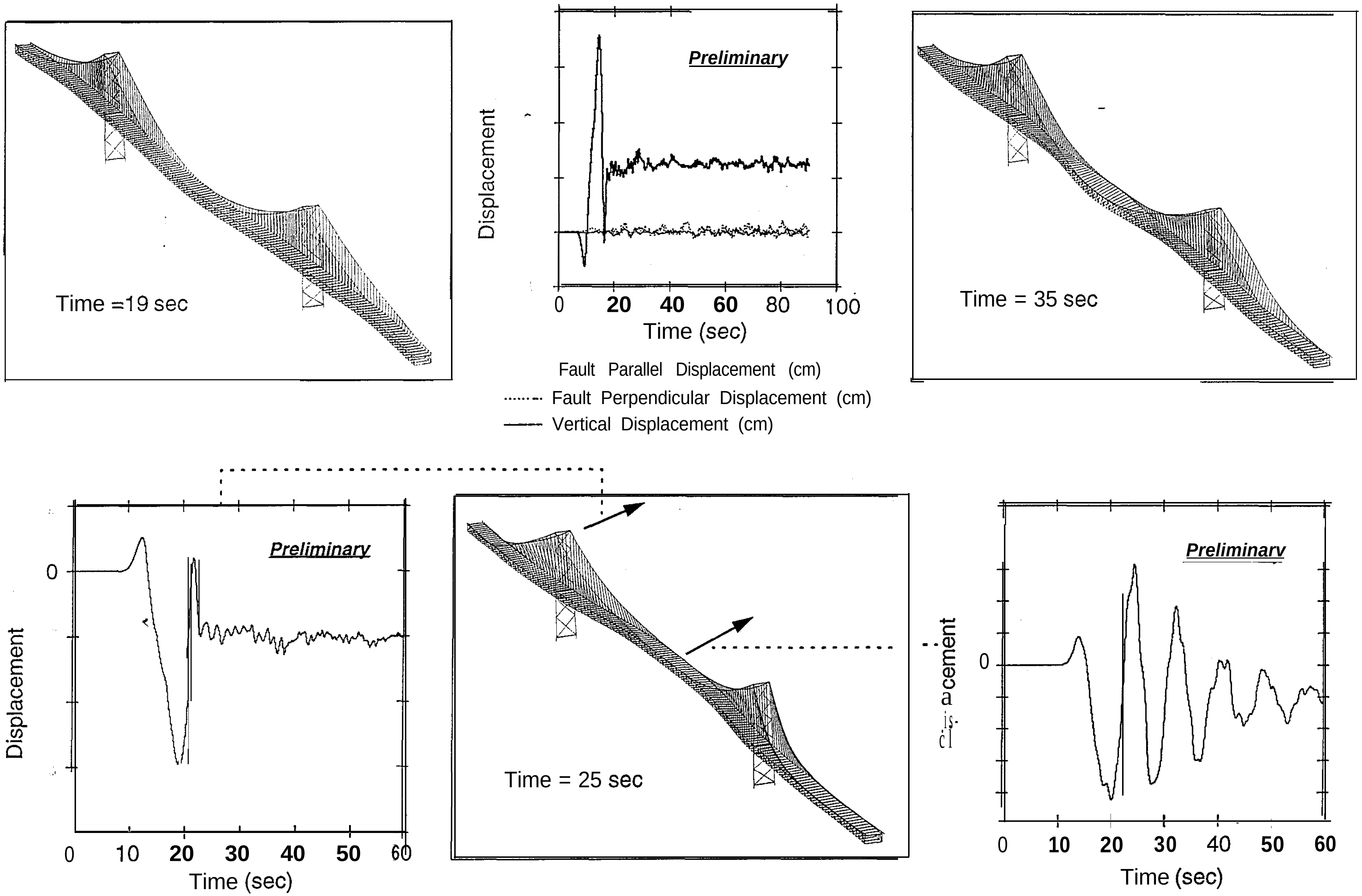
Our CLC proposal had a nontechnical goal: to work toward the development of a stronger long-term strategy for reducing earthquake risk in the Bay Area, and to help define the UC role in that strategy. Our efforts toward that end have been successful, although through interactions with the Southern California Earthquake Center (SCEC) rather than the way that was originally proposed. In addition to technical collaborations, the seismic PIs of the two CLC projects have been instrumental in efforts to develop an integrated, state-wide proposal for an NSF Science and Technology Center to replace SCEC when its 10-year life ends. The goals of that center are consistent with the seismic goals of this project: to apply physics to modeling the earthquake source and wave propagation to estimate hazards.

## Figures

Figure I. A sample calculation from the linear finite-difference wave propagation model for the Bay Area. The first three images show the wave field throughout the San Francisco Bay Area during the evolution of a particular bilateral rupture of the Hayward Fault. The fourth image is a map of peak horizontal velocity calculated for this event. Fifteen seconds after the earthquake initiates at the center of the fault, we see two high-energy zones propagating in opposite directions along the fault. The wavefronts are not circular because the geologic model has spatial variations in seismic velocity. Later, we see energy accumulating in the shallow basins, which keep ringing after the fault rupture stops around 30 seconds after initiation. Calculations such as these will be used to generate low-frequency input into the Bay Bridge model, and will be used to assess the theoretical uncertainties in ground motion due to geologic structures.

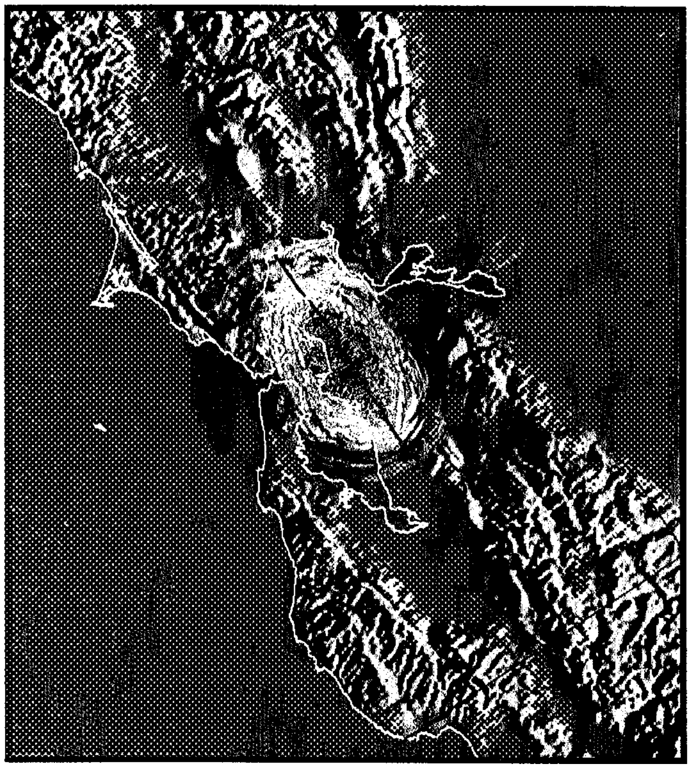
Figure II. A preliminary simulation of the response of the Bay Bridge to a M=7.25 bilateral rupture on the Hayward Fault. The input displacement records are in the center image of the top row. As can be seen from this image, the wave propagation code provides a stable calculation of the near-static offset, which, for this model, is predominantly parallel to the fault and transverse to the bridge. The bridge images show the absolute displacement response of the Bay Bridge, with the amplitude exaggerated to make it visible. At 19 seconds, the primary strain in the bridge is due to the time it takes for the deck to respond to the large transverse motions of the towers. Later images show higher modes such as deck torsion and cable motions. The two time histories on the bottom row show the transverse tower (left) and deck (right) motions. Note that in the coordinate system for the bridge motion calculation, the transverse direction is approximately the negative of the fault parallel direction.

**Bay Bridge Western Span Ground Motions Due to Preliminary Ground Motion (0-1 Hz)**
**For a Particular Hayward Fault Rupture (bi-lateral rupture)**




**Preliminary Numerical Simulation of Bay Bridge Response**

**15 seconds**



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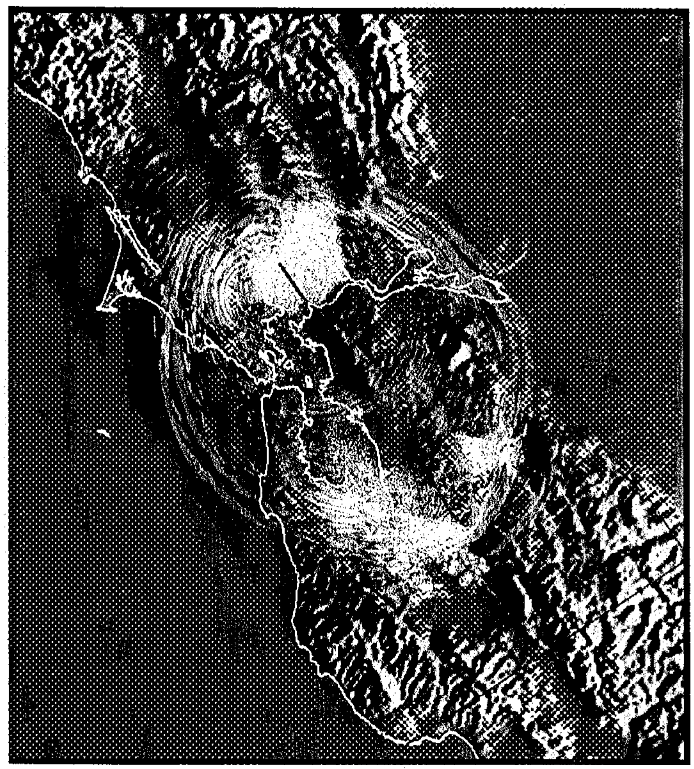
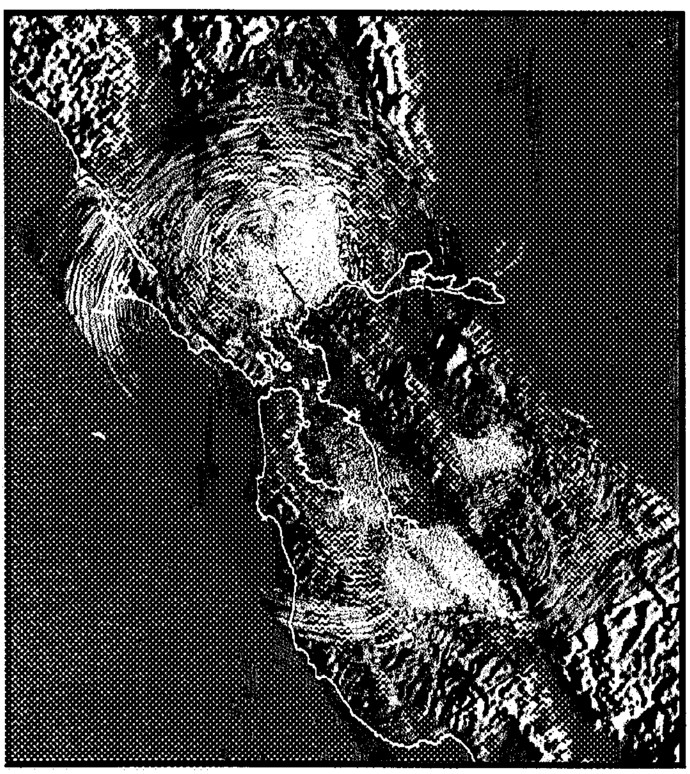
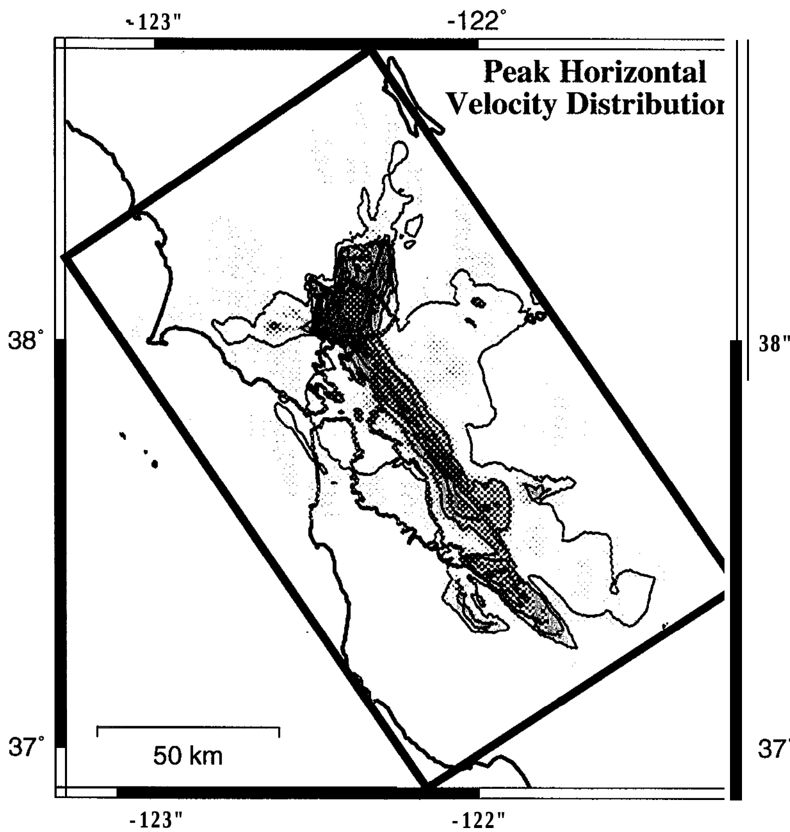


**45 seconds**





## Personnel

In addition to promoting technical interactions, this CLC project provides an opportunity for UC students and staff to have access to computationally based capabilities from LLNL and for LLNL scientists to use data collected by unique UC facilities. Most of these collaborations do not show up in the UC-CLC budget pages. Many of these interactions have taken place over the internet, or are local meetings at UCB, LLNL or even on the Bay Bridge or a drilling barge in the Bay. A second area of interaction has been at the SCEC meetings in southern California, and we have been able to get funding for participation from other sources. The general nature of participation is described below.

LLNL Participants:

> *Paul Kasameyer (LLNL/UCLA): Ground-motion synthesis (0.25 personmonths at UCLA, 2 personmonths at LLNL, Interacted with Jackson, Kagan, and other LLNL participants) 1 trip to UCLA, UCCLC Workshop in San Ramon, CA.
>
> *Larry Hutchings (LLNL/UCSB): Ground-motion synthesis, Bay Bridge instrumentation (2.4 personmonths at LLNL, continuous interactions with Prof. McEvilly, Clymer, LLNL students) 1 trip to Greece for IASPEI meeting, 1 trip to NCEER workshop on Saugenay Earthquake, 8 trips to UCB and 10 trips to Bay Bridges, UCCLC Workshop in San Ramon, CA.
>
> *Shawn Larsen (LLNL/UCB): Wave propagation modeling. (2.0 personmonths at LLNL, 0.4 personmonths at UCB, Collaborated with Prof. Dreger and Prof. Romanowicz, student/post doc Antolik, student Stidham. Logged over 300 e-mail messages to them in one year) , UCCLC Workshop in San Ramon, CA.
>
> *Bill Foxall: Source characterization, rupture mechanics (2 personmonths at UCB, .4 at Livermore, collaborated with Nadeau, Co-PI on related IGPP grants to Kellogg and Politz of UCD and Oglesby, UCSB) 2 trips to SantaBarbara, 2 trips to SCEC annual meeting; 5 meetings about new earthquake center proposal with all CLC PI's, Participating in study of update of Bay Area earthquake probabilities, UCCLC Workshop in San Ramon, CA.
>
> *David McCallen (LLNL/UCB): Code development and applications for stuctural modeling of long cable-stayed bridges.(2.0 personmonths LLNL, 0.4 personmonths UCB, Worked with Prof. Abolhassan Astaneh-Asl his students), UCCLC Workshop in San Ramon, CA.

UCB Faculty/Staff

> **Prof. Douglas Dreger: Bay Area Geological Model and seismic modeling, (worked with Larsen, Nadeau, Prof. Romanowicz).
>
> Prof. Barbara Romanowicz: Responsible for BARD, NCEDC, (worked with Prof. Dreger, student/post doc Antolik, student Stidham, Clymer, Murray, Baxter), UCCLC Workshop in San Ramon, CA.
>
> Prof. Thomas McEvilly: Reponsible for Hayward Fault Network (worked with Hutchings, Clymer), UCCLC Workshop in San Ramon, CA.
>
> Prof Abolhassan Astaneh-Asl: Structural Modeling and performance (1 personmonth), UCCLC Workshop in San Ramon, CA.
>
> Prof. David Brillinger: Developed wavelet variants of point process models and applied them to the series of California earthquakes of magnitudes 5 or greater.

Richard Clymer: Installation, maintanance, and data collection for Bay Bridges network, BARD (4.2 personmonths at UCB and in the field, worked with Hutchings, LLNL students)

Mark Murray:(2.1 personmonths)

D. Ray Baxter:(4.8 personmonths)

UCLA Faculty/Staff

Prof. David Jackson: Earthquake recurrence rates and statistics of historical record, UCCLC Workshop in San Ramon, CA.

Yan Kagan: Earthquake recurrence rates and statistics of historical record (4 personmonths), UCCLC Workshop in San Ramon, CA.

UCB PostDocs/Students

Robert Nadeau (post-doc, Geology and Geophysics): Source characterization, processing Parkfield data, identification and interpretation of characteristic earthquakes from the Parkfield seismic network. (4.7 personmonths, worked with Foxall)

Frederic Schoenberg (graduate student, Statistics): Completed a doctoral thesis in Statistics titled "Assessment of multidimensional point process models", in which he develops a procedure for the assessment of proposed models for marked point processes in time and space, and applied it to the Parkfield data set. (2.3 personmonths, interacted with Prf. Brillinger and Foxall).

Wayne Falk (graduate student, Stuctural Engineering): Research and develop modeling information on structural properties of the components of the west spans of the Bay Bridge. (1.1 personmonths, worked with Prof. Astaneh-Asl, McCallen and other students)

Judy Liu (graduate student, Structural Engineering): Establishing NIKE-3D, a computer analysis code developed at LLNL, at UCB, and doing finite element modeling of components. (1.5 personmonths, worked with Prof. Astaneh-Asl, McCallen and other students)

Sanjay Ravat (graduate student, Structural Engineering): Establishing NIKE-3D, a computer analysis code developed at LLNL, at UCB, and doing finite element modeling of components. (1.3 personmonths, worked with Prof. Astaneh-Asl, McCallen and other students)

Masami Jin (graduate student, Structural Engineering) (1.2 person months)

Kai Wang (undergraduate student): Literature survey and some secretarial aspects of the project (1 personmonth).

Sung-Wook Cho (graduate student): Developing detailed finite element model of main towers and a segment of the stiffening trusses (1.5 personmonths, worked with Prof. Astaneh-Asl, McCallen and other students).

Jack Lopez ( graduate student): Developing global "engineering" model of the entire west spans of the Bay Bridge (4 personmonths).

**Mike Antolik: Comparing predicted to observed ground motions from the 1989 Loma Prieta earthquake using finite difference model developed at LLNL, and is using high performance computers at LLNL (Worked with Larsen and Prof. Dreger).

**Christiane Stidham: Developed the 3D velocity model of the Bay Area that is used in our seismic simulations using finite difference model developed at LLNL (worked with Larsen and Prof. Dreger).

UCLA students

Robert Ge: (Graduate student) Modeling geodetic observations (8 personmonths) Completed Ph.D. thesis.

LLNL undergraduate student program particpants. These students were supported by LLNL and chose to participate in earthquake-related projects because of our CLC efforts.

**Cindy Hayek, San Jose State: Instrumentation, data collection and processing, Developed educational software that uses our computations of ground motion, soil and building response to learn about hazard studies, conducting science experiments, and real world professional applications. (Worked with Hutchings, Clymer, Glenn, McEvilly)

**Jennifer Hollfelder: Data processing (Worked with Hutchings, Clymer, McEvilly)

**Christie Turpin, Sacramento State: Data collection (Worked with Hutchings, Clymer, McEvilly)

**Matt Hoehler, Princeton: Numerical modelling of structures (Worked with Hutchings)

**Edgar Hardy, Southern Mississippi University: Laboratory testing of rocks, (Worked with Hutchings)

**Surina Briscoe,Univ. of Maryland: Implemented a LLNL/UCSB DYNA/3D code for dynamic fault rupture (Worked with Hutchings, Jarpe)

**Martin Glenn San Jose State: Educational Software (Worked with Hutchings)

**Narda Bradman-Florida International University: Numerical modeling of structures.Worked with McCallen)

**Leeann Bent, UC-Davis: Implemented algorithms into the 3D finite-difference seismic wave propagation code.

**Kikuu Mathews, MIT: Educational software package (Worked with Hutchings)

**Charles Hoelzer, SDSU: Wave propagation in rock studies (Worked with Hutchings)

**Patricia Jovena, Princeton: Numerical modelling of structures, wave propagation in rock (Worked with Hutchings and McCallen).

*Funded through UC-DRD funds

**Funded primarily by other projects

Project Title: Advanced Earthquake Hazards Project, Project PI: Paul Kasameyer, Phase I / Year 2

| | | |
|---|---|---|
| **Faculty/Research Staff Salaries** | | **$111,156** |
| Yan Kagan (4 months) | $20,611 | |
| Robert Nadeau (4.7 months) | $12,079 | |
| Richard Clymer (4.7 months) | $29,093 | |
| Mark Murray (2.1 months) | $11,987 | |
| D. Ray Baxter (4.8 months) | $18,386 | |
| Staff | $12,000 | |
| Prof. A. Astaneh-Asl (1 month) | $ 7,000 | |
| Student salaries, tuition, benefits | | $54,844 |
| Fredric Schoenberg (2.3 months) | $ 6,777 | |
| Robert Ge ( 8 months) | $23,067 | |
| Structural Engineering Students: Sung Wook Cho, 1.5 months), Wayne Falk (1.1 months), Masami Jin (1.2 months), Judy Liu (1.5 months), Sanjay Ravat (1.3 months), Kai Wang (1 month) | $25,000 | |
| **Travel Outside UC** | | **$12,914** |
| 1x Conference, St. Louis | $ 1,575 | |
| 1x Seismological Society of America (Mo.)$1185, 1x AGU, San Francisco, $332, , 1x SCEC Meeting, (San Diego) $122, 1x Meeting on Earthquake Hazards methods, (Buffalo), $670 | $ 2,310 | |
| A. Astaneh, J. Liu and C. Cho to attend conferences | $ 6,900 | |
| SSA Meeting, Hawaii | $ 1,053 | |
| Site search and installation, AGU | $ 1,076 | |
| **Travel within UC** | | **$201** |
| 3x UCCLC Workshop, (San Ramon CA), $201 | $201 | |
| **Equipment (Specify items over $5,000)** | | **$59,992** |
| Computer | $ 1,130 | |
| Digital Dec Alpha workstation | $31,700 | |
| Sun Workstation | $ 6,082 | |
| Other | $10,947 | |
| Accelerometers, communication system upgrades | $10,133 | |
| **Supplies, Other** | | **$50,810** |
| Computer time and MIsc. | $ 3,598 | |
| - | $ 1,478 | |
| Research administration, supplies, communications, Mail, stc. | $19,500 | |
| - | $836 | |
| S&E for Installation & maint. of seismometer sites at the Bay bridges, recording system upgrades/repairs, computer usage | $18,487 | |
| - | $ 6,911 | |
| Total Expenditure | | $289,918 |
| Allotted Budget | | $300,000 |
| Carry Over from Year 1 | | $122,616 |
| Available Funds | | $422,616 |
| Carryover As of Nov. 1, 1997 | | $132,698 |

## Publications (published, anticipated, and planned manuscripts, including oral presentations)

Antolik, M., C. Stidham, D. S. Dreger, S. Larsen, A. Lomax, and B. Romanowicz (1997) “2D and 3D Models of Broadband Wave Propagation in the San Francisco Bay Region and Northern Coast Ranges”. UCRL-JC-126069 Abs. *Seis Res Let*., **68**, 328, 1997.

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## Other Support

For this year, the project has received additional direct support of $125K from the LLNL Office of University Relations DRD program. The Bay Bridges instrumentation effort has been aided by a $300K, 3 year grant to UCB from Caltrans for recording and archiving the data from the sensors installed by the CLC project. The BARD Project involves considerable support outside the CLC project; the CLC funding was used to leverage additional funds from EPRI (Electrical Power Research Institute) for 2 receivers, and for NSF/ARI funding, which allowed BARD to acquire six more receivers.

The rapid success in applying the wave propagation codes has been a result of strong collaborations with USGS funded projects of Prof. Douglas Dreger, UCB.

This program benefits from strong interactions with existing LLNL programs. The wave propagation code development was supported in part by LLNL's Comprehensive Test Ban Treaty Program, and by a collaborative venture with several oil industry partners as part of the Advanced Computational Technology Initiative (ACTI). The structural modeling effort takes advantage of algorithms and pre-and post-processing systems developed for the Weapons Programs. Several summer and part-time students were supported by the LLNL student programs.

We expect to leverage the collaborations developed here in to future support. For example, the wave propagation code and geologic model is the basis of new proposals to NASA, NSF, NEHRP, and DOE-OBES. The structural modeling efforts have lead to proposals to commercial entities and to the LLNL Base Engineering Department to develop instrumentation for rapid assessment of structural conditions. Many other successes are anticipated.

## Comments and Suggestions to the CLC program management.

None at this time.

# APPENDIX A

## 3 - HAYWARD FAULT NETWORK

A network of borehole-installed wide dynamic range seismographic stations - the Hayward Fault Network (HFN) - is being developed cooperatively with the U.S. Geological Survey with support from USGS, EPRI, Caltrans, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL, and LBNL (Table 3.1, Figure 3.1). The focus of the network and associated research is to improve working models for this very hazardous but poorly understood fault, and to integrate the data into the real-time monitoring and alert system being developed at the UC Berkeley Seismological Laboratory. After initial operation with portable, stand-alone event recorders, 24-bit data acquisition and communication platforms are now being installed and telemetered data streams are entering the BDSN archives at UCB.

The Hayward fault is somewhat anomalous in its behavior, being a fault zone which is both creeping yet presumably accumulating strain for M7-7.5 earthquakes at recurrence intervals of less than 200 years. New models for the plate boundary geometry in the San Francisco Bay region call for mid-crustal detachment and a central role for the Hayward fault in accumulating the deformation. The base of the seismicity, or brittle-ductile transition, at 10-12 km, is more shallow at the Hayward fault than to the east or west. Its low rate of occurrence of earthquakes (about 10 per year at M>2.5) operates to frustrate its study with conventional instrumentation. Historical seismicity rates, from the various networks operating over the years, suggest that there is sufficient seismicity, perhaps an event per day at a detection threshold around magnitude 0.5 to 1.0 to allow special study of the fault-zone processes. Such a detection sensitivity requires high-gain instrumentation and sophisticated noise mitigation techniques, possible in the East Bay Area only with borehole-installed seismometers.

The network as envisioned will consist ultimately of 24 to 30 stations, 12-15 each north and south of the San Leandro seismic gap, managed respectively by UCB and USGS. Six-component borehole sensor packages designed and fabricated at LBNL's Geophysical Measurements Facility by Don Lippert and Ray Solbau, with three channels of acceleration and three of velocity are being installed in the entire network. The HFN data are also incorporated in real-time into the Rapid Earthquake Data Integration (REDI) Project.

The Bridge Safety Project of the California Transportation Department has made possible installation of sensor packages in 15 boreholes into bedrock at five East Bay bridges cooperatively with L. Hutchings of LLNL. Three of the bridge sites are now telemetered to the Berkeley Seismological Laboratory and as new telemetry links are installed, either with frame-relay links, spread-spectrum radios or cellular phone connections, they will be brought on-line and gathered into the centrally controlled network. Meanwhile, portable recorders are being used at the bridge sites. In a separate but closely-linked Caltrans-supported project, we are working toward installation of permanent power and telemetry to eliminate monthly personnel-intensive visits to the remaining stations for battery and disk changes.

The basic concept for HFN is that, in an urban environment swamped with cultural background noise (traffic & industry vibrations) orders of magnitude above average levels in remote sites, any individual station running on-site detection software has a high probability of being desensitized at any time from the noise and thus will miss many of the small events we need to record at all network stations for high-resolution study of Hayward fault activity. It is totally impractical to telemeter all of the data at the necessarily high sample rates (500 sps, up to four components) to a central site for processing in real-time. To circumvent this problem we employ two countermeasures: (1) the sensors are placed in boreholes as deep as possible (preferably 100 m or more) and in bedrock, for a significant reduction of the surface noise, and (2) representative signals (a single 100 sps vertical component from each station) are processed centrally for the detection of legitimate microearthquakes, and recovery of the full data set for the event from the entire network is accomplished by command from the central site, in a fully automated system. The detector has been running for six months now in an off-line processing mode successfully. The magnitude threshold is approximately 0.0 for small events along the Hayward fault. With a false detection level of about two thirds, on average more than one event per day is recovered (-5.2 per day), satisfying the design goals of the network. As more stations in boreholes are added, the quantity and quality of the data will improve.

HFN is possible because of progress over the last decade in instrumentation, telemetry and computer hardware, allowing implementation of the centrally-controlled local network with very high sample rates (i.e., up to 1000 sps). The Quanterra Q4120 instruments, designed for HFN, have four channels, three with special amplifiers for the accelerometers and continuous and triggered sampling to 1000 Hz. Due to the high sample rates, 38.4 Kbit/second frame-relay digital telemetry is used.

There are now six Q4120-equipped and digitally telemetered HFN stations. With this base we can now make use of the central site triggering capabilities to remotely enable event data recovery from all the stations. We are also currently in the process of securing two new sites, probably very near-surface installations, at Saint Mary's College (already permitted, with frame-relay connection in place) and at the Sobrante Ridge Regional Preserve, to complete the coverage on the east side of the fault.

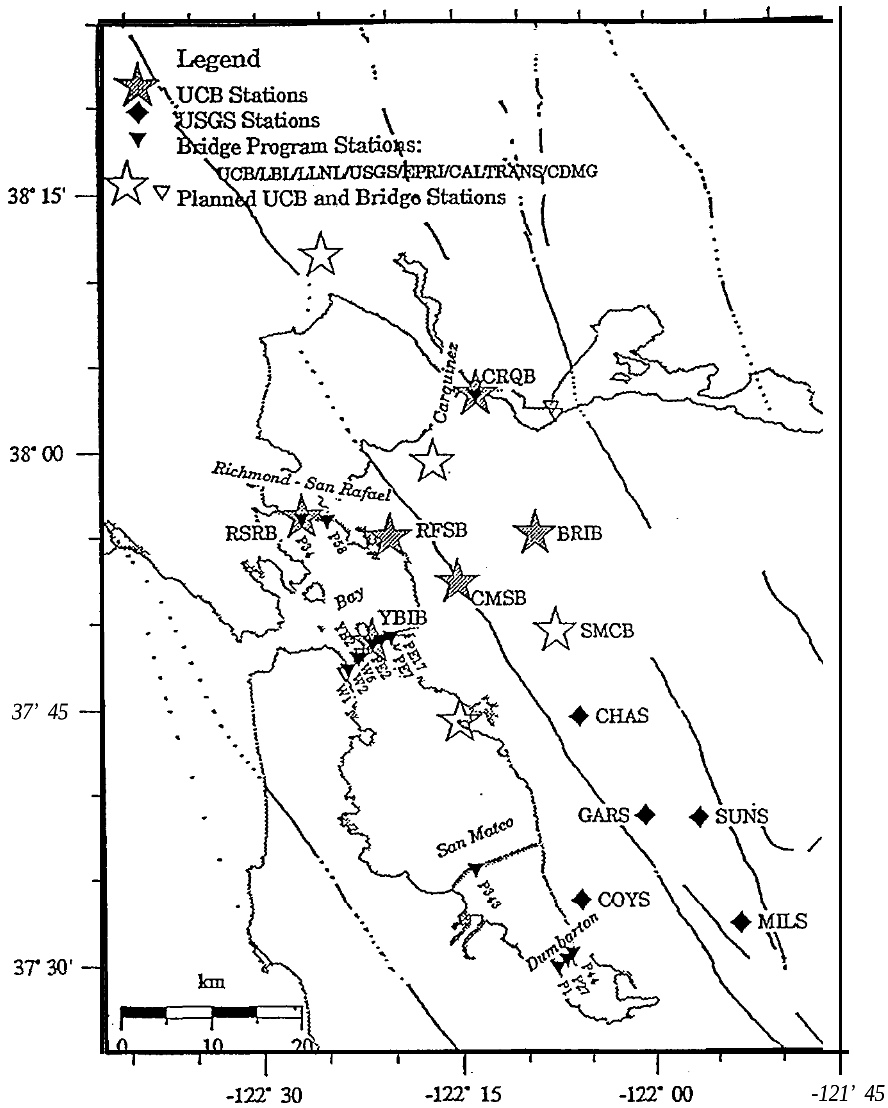



**Figure 3.1:** Map showing the locations of the Hayward fault stations and the Bridge Program Stations. The shaded stars are existing UCB HFN telemetered borehole stations. The solid diamonds are corresponding USGS HFN stations along the southern half of the Hayward fault. The solid triangles are existing Bridge Program stations. Finally, the open stars and triangles are planned UCB and Bridge stations. The planned UCB HFN station (St. Mary's College) will be installed by October 1997. *Courtesy of R. Uhrhammer*

Table 3.i.

## Hayward Fault Network and Bridge Program Stations

| Station | Location | Coordinates (degrees) (NAD27 datum) | Instruments (see Notes) | Date of Upgrade to Telemetry & Q4120 | Comments |
|---|---|---|---|---|---|
| | *HFN Sites:* | | | | |
| CRSB | Carquinez Bridge | 38.05591 N 122.22402 W | Standard (see Note 3) | 3-Jul-96 | |
| RFSB | UCB/Richmond Field Station | 37.91616 N 122.33502 w | Standard | 29-Jun-96 | |
| BRIB | UCB/Russel Reservation | 37.91894 N 122.15062 W | Accelerometers failed. Otherwise standard | 29-Jun-95 | Recording 3 components velocity. |
| CMSB | UCB/Cal Mem. Stadium. | 37.87202 N 122.25060 W | Standard | 19-Dec-94 | |
| YBIB | Yerba Buena Is.. Bay Bridge | 37.81427 N 122.35815 W | Telemetry via radio modems Otherwise standard | 28-Jun-96 | |
| RSRB | Rich./San Raf. Bridge,Pier 34 | 37.9358 N t22.4454 W | standard | 6-Jun-97 | |
| BBEB | Bay Bridge, east approach | 37.82167 N 122.32867 W | No recorder Accelerometers failed. | NA | Off-line 19Oct95 due to briige retrofit. |
| St Mary's College | Moraga | 37.8402 N 122.1056 W | Wilcoxin 731A (accel.) Near-surface installation | Projected Fall '97 | Permitted, to be installed |
| Sobrante Ridge | El Sobrante | 37.970 N 122.257 W | Wikoxin 731A (accel.) Near-surface installation | Projected Fall '97 | To be Permitted and installed |
| | *Bridge Program Sites:* | | | | |
| Pier w2 | Bay Bridge | 37.79120 N 122.38524 W | RefTek 72A-02 (6-chan.) | NA | Recording acceleration, with high/low gain. |
| Pier W5 | Bay Bridge | 37.8010 N 122.3737 W | RefTek 72A-02 (6-chan) | NA NA | Recording 3 comp. accel.. 3 comp. vel. |
| Pier E7 | Bay Bridge | 37.81847 N 122.34688 W | RefTek 72A-07 (3-chan.) | NA | Recording 3 components accel |
| Pier Et7 | Bay Bridge | 37.82086 N 122.33534 W | RefTek 72A-07 (3-chan.) | NA | Recording 3 components accel. |
| Pier 1 | Dumbarton Bridge | 37.49947 N t22.12755 w | RefTek 72A-02 (6-chan.) Accelerometers failed | NA | Recording 3 components deep velocity (228.0 m) |
| Pier 27 | Dumbarton Bridge | 37.50687 N 122.11566 W | RefTek 72A-02 (6-chan.) | NA | Recording 3 components accel. |
| Pier44 | Dumbarton Bridge | 37.51295 N 122.10857 W | RefTek 72A-02 (6-chan.) Accelerometers failed | NA | Recording intermediate (62.5 m.) and deep (157.9 m.) velocity |
| Pier 343 | San Mateo Bridge | 37.59403 N 122.23242 W | Event recorder planned. | NA | Sensor installed; cabling and instrument housing to be installed. |
| Pier 58 | Rich/San Raf. Bridge | 37.93372 N 122.41313 W | Event recorder planned | NA | Sensor and cable installation complete; housing lo be installed. |

Notes: 1. Sensors. Sites equipped with identical 6-component borehole packages cemented into basement rock (unless otherwise noted):

-3 components acceleration (Wilcoxon 731A),

-3 components velocity (Oyo HS1 4.5 Hz geophone)

The accelerometers have failed at some sites (as noted).

2. Initial HFN instrumentation: At most sites. acceleration channels initially recorded on portable event recorders with GPS clocks.
3. Standard HFN Instrumentation: 4-channel Quanterra Q4120 data platforms with GPS clocks and 38.4 K-baud, dedicated frame relay telephone telemetry to UCB data center. recording 3 components acceleration and the vertical velocity component.
4. Standard brkfge program instrumentation: Presently, sites are equipped with stand-alone event recorders. Sites will be uporaded to telephone telemetrv to the Berkelev data center In 1997-98

## Appendix B: The Bay Area Deformation Network

The Bay Area Regional Deformation (BARD) network of permanent, continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area and northern California. It is a cooperative effort of the Berkeley Seismological Laboratory at UC Berkeley (BSL), the US Geological Survey (USGS), and several other academic, commercial, and governmental institutions. Started in 1991 with 2 stations spanning the Hayward fault, BARD now includes 26 permanent stations and will expand to nearly 40 stations in 1998 (Figure 4.1). The principal goals of the BARD network are: 1) to determine the distribution of deformation in northern California across the wide Pacific-North America plate boundary from the Sierras to the Farallon Islands; 2) to estimate three-dimensional interseismic strain accumulation along the San Andreas fault system in the San Francisco Bay area to assess seismic hazards; 3) to provide critical monitoring of faults and volcanoes for emergency response management; and 4) to provide the necessary infrastructure for geodetic data management and processing in northern California in support of related efforts within the BARD Consortium and with surveying, meteorological, and other interested communities.

### Instrumentation

BARD presently includes 26 permanent, continuously operating stations: 11 operated by the BSL (including one with equipment provided by Lawrence Livermore National Lab), 3 operated by the USGS, Menlo Park, California, 2 operated by Trimble Navigation, and 1 by Stanford University. Other stations are maintained by institutions outside of northern California, such as the National Geodetic Survey, the Jet Propulsion Laboratory, and the Scripps Institution of Oceanography, as part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation. In addition, 3 semi-permanent stations are operated by UC Davis (Table 4.1).

In 1996, the BSL acquired 13 Ashtech Z-12 receivers with Dorne-Margolin design choke ring antennas from a combination of federal (NSF), state (CLC), and private (EPRI) funding. Five of these receivers were installed during the past year and six more will be installed during the next year to densify the continuous strain measurements in the San Francisco Bay area and to consolidate the regional geodetic network. One particular focus of the station locations is the profile between the Farallon Islands and the Sierra Nevada in order to better characterize the larger scale deformation field in northern California (Figure 4.1, Table 4.1). The other 2 receivers will be part of Self-Continuous Autonomous Mobile Positioning Stations (SCAMPS) that can be deployed for short intervals within dense local subnets around the Hayward fault and in the north Bay area.

In 1996, researchers from the BSL, the USGS, Stanford University, LLNL, UC Davis and UC Santa Cruz formed a consortium of institutions involved in studies of the tectonic deformation in the San Francisco Bay area and northern California. Members of the BARD consortium agreed to pool existing resources and coordinate development of new ones in order to advance an integrated strategy for improving the temporal and spatial resolution of the strain field. They agreed in principle to the continued development of the network of permanently deployed GPS receivers, to the development and maintenance of a pool of GPS receivers for campaign-mode operations that, when not used in campaigns, will be deployed in semi-permanent mode in the San Francisco Bay area, to archiving of all data at the NCEDC, and to the development of a coordinated data analysis facility that will process permanent, semi-permanent, and campaign-mode data.

All these stations, with the current exception of SUTB (Sutter Buttes), are co-located with BDSN broadband seismic stations and take advantage of existing continuous telemetry. Each site features the choke ring antenna design, mounted to a reinforced concrete pillar, approximately one meter above local ground level.

The UCB Seismological Laboratory currently maintains and retrieves data from 11 Ashtech Z-12 receivers. Data from 10 of these sites is collected at 30-second intervals, transmitted continuously over serial connections, collected into 24-hour raw serial files and processed daily. The serial connections to seven sites use frame relay technology, one site (Tiburon) has a direct radio link to Berkeley and two sites (Sutter Buttes and Farallon) use a combination of radio and frame relay technologies. We have developed software to interpret and collect the raw serial output into hourly files, which is then converted to the standard interchange RINEX format using software provided by NGS and UNAVCO. Data from the Hopland site is stored in 24-hour raw receiver files and retrieved via dial-up telephone lines using PC scripts we adapted from scripts provided by SIO. In 1996-1997 we converted four of our sites from dial-up telemetry to continuous serial telemetry; early in the coming year Hopland will be converted to continuous telemetry using a combination of radio and frame relay.

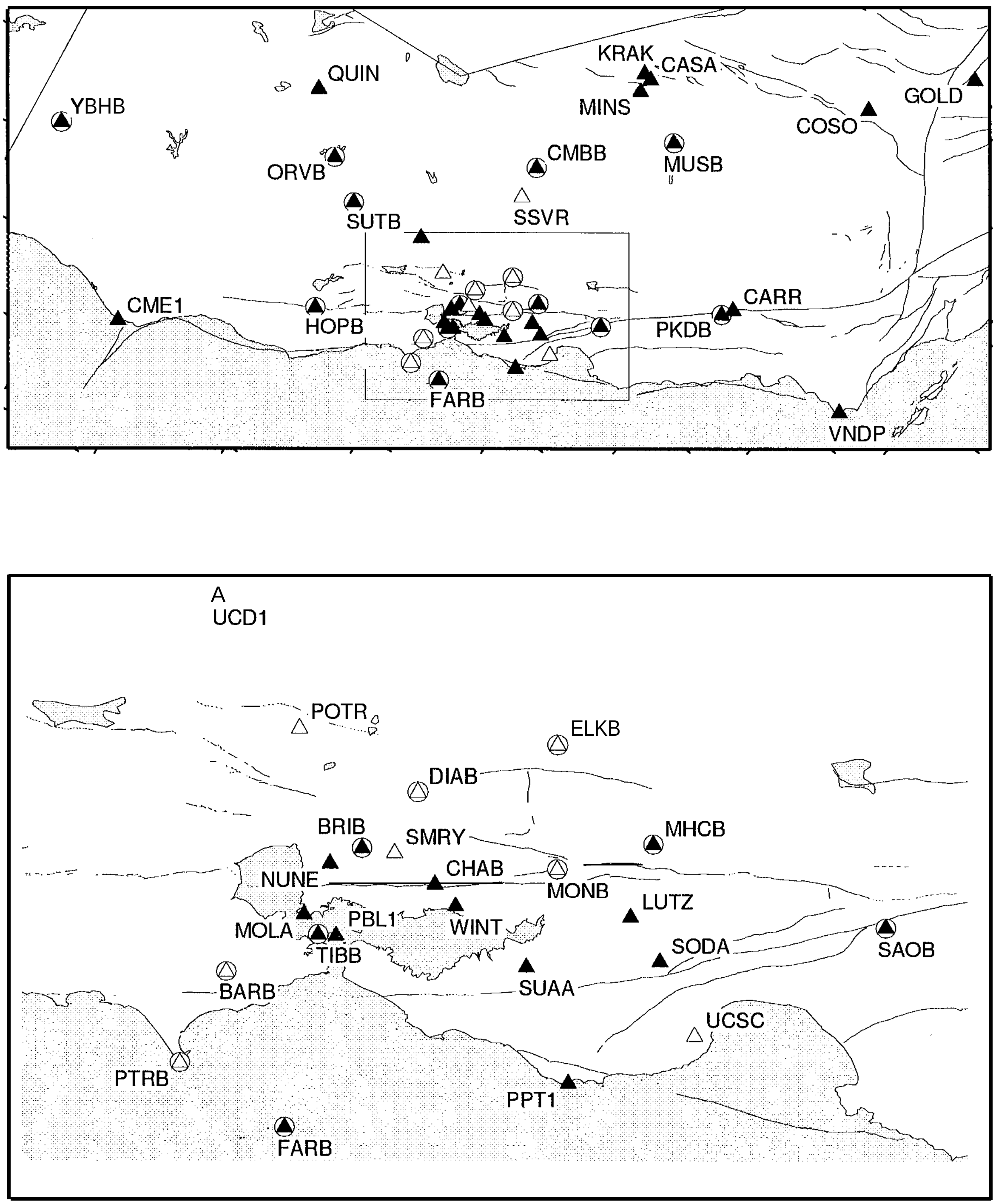
Ten current GPS sites are co-located with broadband seismometers and Quanterra data collectors. With the support of IRIS we have begun development of software for the Quanterra that will allow the storage and retrieval of the continuous serial output of Ashtech and Trimble GPS receivers during and after a telemetry outage. In the coming year this software will be completed, tested and submitted to UNAVCO for general public distribution. Data Archival and Distribution

The raw and RINEX data files are imported in a timely fashion into the UCB/USGS Northern California Earthquake Data Center (NCEDC) data archive maintained at UCB (Romanowicz et al., 1994), where they are immediately accessible to all BARD participants and other members of the GPS community through Internet, both by the World Wide Web (http://quake.geo.berkeley.edu/bard/bard.html) and by anonymous ftp. Data and ancillary information about BARD sites are also made compatible with standards set by the International GPS Service (IGS), which administers the global tracking network used to estimate precise orbits and has been instrumental in coordinating the efforts of other regional tracking networks. The USGS imports data daily from the USGS and Trimble stations into the NCEDC. In addition, the BSL automatically retrieves data from other continuously operating stations in northern California from other GPS archives, such as at SIO, JPL, and NGS, using modified UNIX scripts provided by SIO. The NCEDC currently archives nearly all high-precision continuous GPS measurements collected in northern California. Many of the BARD sites have been added by the NGS to their database of CORS sites after having established their locations in the WGS 84 coordinate system. This makes the data more useful to the general surveying community, another goal we are pursuing through discussions at meetings of the Northern California GPS Users Group.

**Data Analysis**

The data from the BARD sites generally are of high quality and are measuring relative horizontal positions at the 2-5 mm level. The 24-hour RINEX data files are processed with an automated system using high-precision IGS orbits daily. The typical RMS scatter in baseline length is 2-5 mm. Baseline measurements typically have 3-5 mm RMS scatter about a linear fit to changes in north and east components and the 15-25 mm RMS scatter in the vertical component . The 3-5 times greater scatter in the vertical is often seen in GPS measurements and is usually attributed to atmospheric effects and to the inability of the receivers to track below the horizon. Data are currently processed automatically using the latest available high-precision orbits distributed by IGS, either final orbits (available within 10 days), rapid orbits (available within 1 day), or predicted orbits (available on the same day). This processing is used to provide quality control, showing possible site problems or dropouts (e.g., CMBB, MINS, and QUIN), and to detect anomalous deformation at the cm-level in the horizontal and 3-cm-level in the vertical.

With the help of CLC funding, the principal focus of the BSL effort is to develop real-time analysis techniques that will enable rapid determinations (~minutes) of motion following major earthquakes to complement seismological information and aid determinations of earthquake location, magnitude,geometry, and strong motion. Towards that goal, we have begun to process data available within 1 hour of measurement from the 10 continuous telemetry stations, and 3 U.S. Coast Guard stations. The data are binned into 1 hour files and processed simultaneously. The scatter of these hourly solutions is much higher than the 24-hour solutions, 10 mm in the horizontal and 30-50 mm in the vertical; however, displacements 3 times these levels should be reliably detected.




Operational (solid triangles) and planned (open triangle) BARD stations. Figure courtesy of Mark Murray