# Berkeley Seismological Laboratory

Land Uplift in the Santa Clara Valley, 1992-1998



relative uplift [mm]

# Annual Report
# July 2001 - June 2002

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# Introduction

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# Director's Report

## 1. Background and Facilities

The Berkeley Seismological Laboratory (BSL), formerly the Berkeley Seismographic Station (BSS), is the oldest Organized Research Unit (ORU) on the U. C. Berkeley campus. Its mission is unique in that, in addition to research and education in seismology and earthquake-related science, it is responsible for providing timely information on earthquakes (particularly those that occur in northern and central California) to the U.C. Berkeley constituency, the general public, and various local and state government and private organizations. The BSL is therefore both a research center and a facility/data resource, which sets it apart from most other ORUs. A major component of our activities is focused on developing and maintaining several regional observational networks, and participating, along with other agencies, in various aspects of the collection, analysis, archival and distribution of data pertaining to earthquakes, while maintaining a vigorous research program on earthquake processes and Earth structure. In addition, the BSL staff spends considerable time with public relations activities, including tours, talks to public groups, responding to public enquiries about earthquakes and, more recently, World-Wide-Web presence (http://www.seismo.berkeley.edu/seismo/).

U.C. Berkeley installed the first seismograph in the Western Hemisphere at Mount Hamilton (MHC) in 1887. Since then, it has played a leading role in the operation of state-of-the-art seismic instruments and in the development of advanced methods for seismic data analysis and interpretation. Notably, the installation, starting in 1927, of Wood-Anderson seismographs at 4 locations in northern California (BKS, ARC, MIN and MHC) allowed the accurate determination of local earthquake magnitude ($M_L$) from which a unique historical catalog of regional earthquakes has been maintained to this day, providing crucial input to earthquake probabilities studies.

Over the years, the BSS continued to keep apace of technological improvements. The first centrally telemetered network using phone lines in an active seismic region was installed by BSS in 1960. The BSS was the first institution in California to operate a 3-component "broadband" system (1963). Notably, the BSS played a major role in the early characterization of earthquake sources using "moment tensors" and source-time functions, and made important contributions to the early definitions of detection/discrimination of underground nuclear tests and to earthquake hazards work, jointly with UCB Engineering. Starting in 1986, the BSS acquired 4 state-of-the-art broadband instruments (STS-1), while simultaneously developing PC-based digital telemetry, albeit with limited resources. As the telecommunication and computer technology made rapid progress, in parallel with broadband instrument development, paper record reading could be completely abandoned in favor of largely automated digital data analysis.

The current modern facilities of BSL have been progressively built over the last 12 years, initiated by significant "upgrade" funding from U.C. Berkeley in 1991-1995. The BSL currently operates and acquires data, continuously and in real-time, from over 40 regional digital seismic stations, including 20 located in boreholes, 21 permanent GPS stations of the BARD network, and 2 electromagnetic stations. The seismic data are fed into the BSL real-time processing and analysis system and are used in conjuction with data from the USGS NCSN network in the joint earthquake notification program for northern California, started in 1996. This program capitalizes on the complementary capabilities of the networks operated by each institution to provide rapid and reliable information on the location, size and other relevant source parameters of regional earthquakes. In recent years, a major emphasis in BSL instrumentation has been in densifying the state-of-the-art seismic and geodetic networks, while a major on-going emphasis in research has been the development of robust methods for quasi-real time automatic determination of earthquake source parameters and predicted strong ground motion, using a sparse network combining broadband and strong motion seismic sensors, as well as permanent geodetic GPS receivers.

The backbone of the BSL operations is a regional network of 20+ digital broadband and strong motion seismic stations, the Berkeley Digital Seismic Network (BDSN),

with continuous telemetry to UC Berkeley. This network provides the basic regional data for the real-time estimation of location, size and rupture parameters for earthquakes of M 3 and larger in central and northern California, within our Rapid Earthquake Data Integration (REDI) program. It also provides a fundamental database for the investigation of three-dimensional crustal structure and its effects on regional seismic wave propagation, ultimately crucial for estimating ground shaking for future earthquakes. Most stations also record auxiliary temperature/pressure channels, valuable in particular for background noise quality control. Complementing this network is a 20+ station "high-resolution" network of borehole seismic sensors along the Hayward Fault (HFN), operated jointly with the USGS/Menlo Park and linked to the Bridge Safety Project of the California Department of Transportation, which has made possible the installation of sensor packages at 15 bedrock boreholes at 5 east-bay bridges in collaboration with LLNL. A major science goal of this network is to collect high signal-to-noise data for microearthquakes along the Hayward Fault to gain insight into the physics that govern fault rupture and its nucleation. The BSL is also involved in the operation and maintenance of the Parkfield borehole seismic array (HRSN), which is yielding enlightening results on quasi-periodic behavior of microearthquake clusters and important new constraints on earthquake scaling laws and is currently playing an important role in the characterization of the site for the future San Andreas Fault Observatory at Depth (SAFOD). Since April 2002, the BSL is also involved in the operation of a permanent broadband ocean bottom station, MOBB, in collaboration with MBARI (Monterey Bay Aquarium Research Institute).

In addition to the seismic networks, the BSL is involved in data archival and distribution for the permanent geodetic BARD (Bay Area Regional Deformation) Network as well as the operation and maintenance, and data processing of 21 out of its 70+ sites. Whenever possible, BARD sites are collocated with BDSN sites in order to minimize telemetry costs. In particular, the development of analysis methods combining the seismic and geodetic data for the rapid estimation of source parameters of significant earthquakes has been one focus of BSL research.

Finally, two of the BDSN stations also share data acquisition and telemetry with 5-component electro-magnetic sensors installed with the goal of investigating the possibility of detection of tectonic signals.

Archival and distribution of data from these and other regional networks is performed at the Northern California Earthquake Data Center (NCEDC), operated at the BSL in collaboration with USGS/Menlo Park. The data reside on a mass-storage device (2.5 Terabyte capacity), and are accessible "on-line" over the Internet

(`http://www.quake.geo.berkeley.edu`). Among others, data from the USGS Northern California Seismic Network (NCSN), are archived and distributed through the NCEDC. The NCEDC also maintains, archives and distributes the ANSS/CNSS earthquake catalog.

Core University funding to our ORU provides salary support for 3 field engineers, one computer expert, 2 data analysts, 1 staff scientist and 2 administrative staff. This covers the basic needs of the operations of the BDSN and seed funding for our other activities. All other programs are supported through extra-mural grants primarily from the USGS and NSF, and in the past year, the Office of Emergency Services (OES). We acknowledge valuable recent contributions from other sources such as Caltrans, the CLC program, PEER, as well as our Earthquake Research Affiliates.

## 2. Highlights of 2001-2002

### 2.1 Infrastructure and Earthquake Notification

Three major projects of the BSL deserve attention in 2001-2002: CISN, "Mini-PBO", and the ocean bottom observatory MOBB.

A focus of the past year has been the planning and initial implementation of the BSL component of the CISN (California Integrated Seismic Network), with support in FY'02 (received in April 2002) from the State of California through the Office of Emergency Services (OES) (Chapter 3).

A major goal of the CISN is to ensure a more uniform system for earthquake monitoring in California, through the improvement of seismic infrastructure in northern California and continued maintenance of the TriNet system in southern California. Another major goal is to integrate the earthquake monitoring and reporting efforts in the State, using compatible software and creating a single catalog. A present focus is to improve the robustness of statewide rapid notification and work with the California OES and other emergency responders to maximize the use and benefit of this real time seismic information.

In anticipation of the pending funding, BSL staff conducted searches and surveys to identify potential sites for new broadband stations, two of which have been selected and permitted, and will be installed as soon as the equipment becomes available. With very little time to spend the funds from OES in FY'02 (3 months), the BSL purchased equipment for 5 BDSN sites, and focused efforts on the development of software to re-design the USGS/UCB joint earthquake notification system and move towards merging the systems now in operation at each of the two institutions. Initial steps have been taken towards exchanging data in real-time with southern California, involving 10 stations in each sub-region.

BSL staff have spent considerable efforts in organizational activities for CISN, notably by participating in the CISN Project Management Group (Gee) and the Standards Committee (Neuhauser-chair, Gee, Lombard). Romanowicz rotated off as chair of the CISN Steering Committee, but still remains involved. The CISN also represents California as a designated region of ANSS (Advanced National Seismic System) and the BSL is actively involved in planning activities for the ANSS.

This past year has been marked by a climax in the installation efforts towards the "Mini-PBO" project (Chapter 9), a project supported partly by a grant from the NSF/MRI program, in collaboration with CIW, UCSD and USGS/Menlo Park, with matching from UCB and these other institutions as well as Caltrans (`http://www.seismo.berkeley.edu/seismo/bdsn/mpbo_overview.html`). This project's focus is the installation of a network of multi-parameter stations in the San Francisco Bay Area to monitor the evolution of tectonic strain in time and space - a pilot project for the Plate Boundary Observatory (PBO) currently being planned in the framework of an NSF/MRE proposal. "Mini-PBO" instrumentation comprises 3 component borehole strainmeters and seismometers, GPS receivers and auxiliary sensors (such as pore pressure, temperature, and tilt). The data are telemetered to UC Berkeley and distributed through the NCEDC. The first two holes were drilled in early summer 2001 and instrumented in 2002. Three additional holes were drilled in the summer of 2002, with considerable involvement of BSL staff (Murray, Basset, W. Johnson, Karavas) and are currently in various stages of instrument installation. The initial goal of 10 stations has been reduced to 6 due to budgetary constraints related to considerable cost-overruns in drilling. The plan is for the 6th and last hole to be drilled with Caltrans's help in the Fall of 2002.

The MOBB (Monterey Ocean bottom Broad Band observatory) is a collaborative project between the BSL and MBARI and builds upon the experience gained in 1997 through the MOISE project, which involved the temporary deployment of a broadband ocean bottom system in Monterey Bay. MOBB is now a permanent installation and comprises a broadband seismic package (Guralp CMG-1), a battery and recording package, as well as auxiliary sensors: a current-meter and a DPG (differential Pressure Gauge). The system was assembled and tested at BSL in early 2002, and successfully deployed in April 2002 (Chapter 10). In particular, extensive testing and seismometer insulation procedures were developed at Byerly Vault on the UCB campus prior to deployment (Chapter 11).

In the past year, the BSL has been closely involved in the coordination of site characterization for the SAFOD drilling project in the Parkfield area (Chapter 6). In particular, data from the new HRSN borehole site at CCRB, located 2 km south of the target drilling site, is recording signals from the pilot drilling project which may prove crucial for guiding drilling of the SAFOD hole. The new earthquake triggering scheme for the HRSN network has also been finalized, with the goal of reducing the bandwidth necessary for data telemetry to BSL.

Other accomplishments in the past year include the deployment of a new BDSN station (HUMO - Chapter 4) in southern Oregon, in collaboration with USGS/NSN and IRIS programs, and a new BARD station at OHLN (Ohlone Park), the first GPS station to be mounted on top of a Mini-PBO borehole (Chapter 8). A single frequency (L1) GPS receiver profile has been installed across the Hayward Fault, with assistance from UNAVCO engineers, to investigate the resolution power of this cost-effective way to monitor creep on the fault.

The NHFN network project has seen the upgrade of the infrastructure of 7 stations on the Bay Bridge (Chapter 5), in anticipation of the deployment of the Quanterra recording systems and the development of an algorithm to identify highly similar microearthquakes on the Hayward Fault based on complex spectral phase coherency.

On the NCEDC front (Chapter 13), we continue archiving and distribution on-line of data from expanding BDSN, NHFN, HRSN, BARD, Mini-PBO, and other networks and data collections in northern California. A notable addition is the continuous acquisition and archiving of broadband data from 4 stations operated by the University of Nevada, Reno, and 7 stations operated by the USGS Menlo Park. The USGS "low frequency" geophysical time series data collection (strain, creep, magnetic field, water level, etc.) is now accessible in standard MiniSEED format and instrument responses are available for over 90% of the archived channels. The NCEDC also started to archive and make publically available the state-of-health channels for the BDSN/NHFN/MPBO stations. The NCEDC is participating in the UNAVCO-sponsored GPS Seamless Archive Centers (GSAC) initiative, which is developing common protocols and interfaces for the exchange and distribution of continuous and survey-mode GPS data, and is now both a primary provider for BARD/BSL data, a wholesale collection point for other northern California GPS data, and a retail center for all GSAC data.

The BSL continues to collaborate with the USGS/Menlo Park in the generation of ShakeMap for northern California and has been developing and implementing successive upgrades to this system, integrated within the REDI environment (Chapter 12). ShakeMap is calculated routinely for magnitude 3.5 and larger events in northern California. Any magnitude 5.0 or larger will now also trigger the finite-fault processing.

Finally, the BSL has taken steps to use automatically produced moment magnitude ($M_w$), when available, to supplement estimates of local magnitude ($M_L$), which is

particularly useful in the case of significant earthquakes. $M_w$ has been routinely produced within the REDI system for many years, but, until now, not broadcast as the "official magnitude", due in part to questions about the reliability of the automatic solutions. In the past year, the robustness of the moment tensor codes has been improved, facilitating the transition to official broadcasting.

## 2.2   Research Accomplishments

Chapter 15 documents the main research contributions of the last year. Research at the BSL spans a broad range of topics, from the study of microseismicity at the local scale to global deep earth structure, and includes seismological, geodetic and remote sensing (InSAR) techniques.

In this past year, Nadeau and collaborators have continued investigation of fault zone characteristics from the analysis of microearthquakes at Parkfield, and extended their scaling of recurrence times and moments of microearthquakes over 15 orders of magnitude in seismic moment (15.1). They have also been involved in determining the detailed seismic structure around the future site of the SAFOD. These microseismicity techniques are now also being extended to the study of faults in the San Francisco Bay Area (15.2) and to the investigation of the brittle-ductile transition zone and its rheological properties (Rolandone et al.; (15.3). At a very different, global scale, Romanowicz and Ruff re-examined the scaling of moment to length of large strike-slip earthquakes and found that the data fall into two distinct classes indicative of stronger (mostly oceanic) or weaker (mostly continental) faults (15.4).

For the second year, Uhrhammer has been engaged in a major effort to transcribe Berkeley historical earthquake data dating back to 1910, and stored on cards or paper records, to computer readeable format, with the goal of obtaining more complete seismicity catalogs and better characterize the evolution of seismicity with time and space. An initial focus on the San Francisco Bay Area (15.5) is being extended to northern California (15.6). Five undergraduate students have been involved in this project.

A study by Freed has investigated earthquake triggering of other earthquakes on the San Andreas Fault in southern California (15.7).

In a novel application, Schmidt and Bürgmann have used InSar data to study land uplift and subsidence in the Santa Clara Valley, highlighting the spatial complexity of the aquifer system (15.8), while Johanson and Bürgmann are using InSar to detect slow earthquakes on the creeping sections of the San Andreas Fault system (15.9). Murray is engaged in resurveing 40 GPS monuments that were last surveyed in 1993-95 to further characterize crustal deformation in the northern San Andreas Fault system (15.10) and D'Alessio and collaborators are using GPS in survey mode to monitor motion on the Hayward Fault (15.11), and obtain a creep rate of 4.2 mm/year at the Berkeley Memorial Stadium. The BSL has also shared its expertise by collaborating in the deployment of a new regional continuous GPS network in northern Italy, around the epicenter of the damaging 1976 Friuli earthquake (15.12).

Several studies of earthquakes at the regional scale are reported: an investigation of the influence of fluids on faulting at Long Valley Caldera by Templeton and Dreger (15.13); a study of the mechanisms of major aftershocks of the 1999 Chi-Chi earthquake in Taiwan by Chi and Dreger (15.14); adaptation of the BSL real time moment tensor techniques to the monitoring of nuclear explosions in the framework of the International Monitoring System (Hellweg et al., 15.15); and the on-going development of a method to locate the sources of continuous low-frequency background Earth oscillations (Rhie and Romanowicz, 15.16).

In a transition to studies of Earth structure, Rhie and Dreger (15.17) report on their waveform modeling of the seismic velocity structure in Northern California. At the global scale, we report progress in global anelastic tomography, resulting in a new model of attenuation in the upper-mantle, which has revealed the connection of lowermost mantle "superplumes" with upwelling regions in the upper mantle and hotspots (Gung and Romanowicz, 15.17); with Gung and Panning, we have started to investigate radial anisotropy at the global scale (15.18), and have found that discrepancies in different global tomographic models of the upper mantle can be reconciled if anisotropy beneath lithospheric roots (depth range 250-400km) is considered; we have also started investigating anisotropy at greater depths in the mantle and extended our S modeling techniques to include inversion for P velocity (Panning and Romanowicz, 15.19). Rousset and Romanowicz are developing a method based on a neigbourhood algorithm to investigate the range of plausible models for degree 2 heterogeneity in density in the mantle (15.20); with Toh and Capdeville, we are making progress in exploiting the rich capabilities of the coupled mode-spectral element method to study complex 3D structure at the base of the mantle (15.21;15.22); finally, with Tkalcić, we documented sharp, uncorrelated, lateral variations in P and S velocities at the base of the mantle(15.23).

## 3.   Acknowledgements

been appointed Associate Director of the BSL. In particular, Doug has assumed overall responsibility, with help from Bob Nadeau, for the HRSN and NHFN programs, following Professor McEvilly's death.

I also wish to specially thank the individuals who regularly contribute to the smooth operation of the BSL facilities: André Basset, Sierra Boyd, Rich Clymer, Doug Dreger, John Friday, Lind Gee, Wade Johnson, Bill Karavas, Pete Lombard, Rick McKenzie, Mark Murray, Bob Nadeau, Doug Neuhauser, Charley Paffenbarger, David Rapkin, Cathy Thomas, Bob Uhrhammer, and Stephane Zuzlewski.

Eleanor Blair, Heather Read and Christina Jordan continue to provide valuable support to the administration of our lab, with help from Patricia Villa. The BSL administrative office has continued to assist the EPS department administrative personnel, in a continued period of transition in that office. We are also grateful to Ruth Saha, who helped out during a period of high demand.

In 2001-2002, there have been some changes in BSL personnel. Dr Fumiko Tajima left in May 2002 to become a professor at Hiroshima University in Japan. Hrvoje Tkalčić also left in May for a post-doctoral position in sunny San Diego. Steve Chu graduated in December 2001 and left in May to work for a start-up company. We also experienced some turnover in the Adminstrative office, with the departure of Keia Shipp and Aric Mayer.

We welcome three new post-docs at the BSL: Maurizio Battaglia, Andy Freed, and Frederique Rolandone. We also welcome four new staff members: Heather Read and Patricia Villa joined the adminstrative office, Cathy Thomas became part of the field engineering team, and Jim Yan joined the BSL as a programmer. Unfortunately, because of the temporal limitations of CISN funding, Jim Yan left at the end of June.

I also wish to thank our undergraduate assistants S. Chu, J. Epstein, T. Fournier, L. Krain, K. Spiller, G. Treves, and M. Wilmarth for their contributions to our research and operational activities. I am particularly thankful to Lind Gee and Christina Jordan for their help in putting together this Annual Report.

Lane Johnson retired in June 2002 from his teaching position in the Department of Earth and Planetary Science. He will continue research activities at LBNL. I wish to thank him in particular for his role as Acting Director of the BSL during my sabbatical in the spring of 2002 and wish him well in his retirement.

Finally, I wish to express my deep sorrow upon Professor Tom McEvilly's death (Chapter 2). Professor McEvilly passed away on 02/22/2002 after a courageous fight with cancer. Tom's death is a considerable loss for the BSL. We miss his leadership in research, in recent years focused on the Parkfield program, and his cheerful and energizing presence.

The Annual Report of the Berkeley Seismological Laboratory is available on the WWW at `http://www.seismo.berkeley.edu/seismo/annual_report/`.

Barbara Romanowicz
Sept 10, 2002

# 4.  Glossary of Common Acronyms

Table 1.1: Standard abbreviations used in this report.

| Acronym | Definition |
|---------|------------|
| AGU | American Geophysical Union |
| ANSS | Advanced National Seismic System |
| BARD | Bay Area Regional Deformation |
| BDSN | Berkeley Digital Seismic Network |
| BSL | Berkeley Seismological Laboratory |
| BSS | Berkeley Seismographic Station |
| CISN | California Integrated Seismic Network |
| CGS | California Geological Survey |
| CLC | Campus Laboratory Collaboration |
| CNSS | Council of the National Seismic System |
| EM | Electromagnetic |
| EPRI | Electric Power Research Institute |
| FBA | Force Balance Accelerometer |
| FIR | Finite Impulse Response |
| FRAD | Frame Relay Access Device |
| GPS | Global Positioning System |
| HFN | Hayward Fault Network |
| HRSN | High Resolution Seismic Network |
| IGS | International Geodetic Service |
| IMS | International Monitoring System |
| InSAR | Interferometric Synthetic Aperture Radar |
| IRIS | Incorporated Research Institutions for Seismology |
| ISC | International Seismological Center |
| ISTAT | Integrating Science, Teaching, and Technology |
| JPL | Jet Propulsion Laboratory |
| LBNL | Lawrence Berkeley National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| MBARI | Monterey Bay Aquarium Research Institute |
| MHH | Murdock, Hutt, and Halbert |
| MOBB | Monterey Ocean bottom BroadBand observatory |
| MOISE | Monterey Bay Ocean Bottom International Seismic Experiment |
| MPBO | Mini-Plate Boundary Observatory |
| MRI | Major Research Initiative |
| MRE | Major Research Equipment |
| MT | Magnetotelluric |
| NCEDC | Northern California Earthquake Data Center |
| NCSN | Northern California Seismic Network |
| NEHRP | National Earthquake Hazards Reduction Program |
| NEIC | National Earthquake Information Center |
| NHFN | Northern Hayward Fault Network |
| NGS | National Geodetic Survey |
| NSF | National Science Foundation |
| NSN | National Seismic Network |
| OES | Office of Emergency Services |
| ORU | Organized Research Unit |
| PBO | Plate Boundary Observatory |
| PEER | Pacific Earthquake Engineering Center |
| PH | Pilot Hole |
| PPE | Parkfield Prediction Experiment |

Table 1.1: *continued*

| Acronym | Definition |
|---------|-----------|
| PSD | Power Spectral Density |
| REDI | Rapid Earthquake Data Integration |
| SAF | San Andreas Fault |
| SAFOD | San Andreas Fault Observatory at Depth |
| SAR | Synthetic Aperture Radar |
| SCEC | Southern California Earthquake Center |
| SCEDC | Southern California Earthquake Data Center |
| SCIGN | Southern California Integrated GPS Network |
| SEED | Standard for the Exchange of Earthquake Data |
| SHFN | Southern Hayward Fault Network |
| SIO | Scripps Institutions of Oceanography |
| SNCL | Station Network Channel Location |
| SSA | Seismological Society of America |
| STP | Seismogram Transfer Program |
| UCB | University of California at Berkeley |
| UNAVCO | University NAVSTAR Consortium |
| UrEDAS | Urgent Earthquake Detection and Alarm System |
| USGS | United States Geological Survey |

# Chapter 2

# In Memoriam - Thomas V. McEvilly



Figure 2.1: Tom McEvilly (1934-2002). Photograph courtesy of Lawrence Berkeley National Laboratory.

# 1.   Introduction

Thomas Vincent McEvilly died on February 22, 2002. Tom was a valuable member of the Berkeley Seismological Laboratory and the Department of Earth and Planetary Science.

Tom contributed to the BSL in many ways - through important seismological research, through the development of several seismological networks and observational practices, and through service as Assistant Director from 1968 to 1989 and several stints as Acting Director (most recently from February 1 to May 31, 2001). His leadership in the development of the Parkfield High Resolution Seismic Network, the Hayward Fault Network, and Mini-Plate Boundary Observatory was critical to the success of these projects and his influence continues in these efforts today.

Tom's many achievements have been remembered in obituaries written by Lane Johnson for the *Seismological Society of America* (*Johnson*, 2002) and Bruce Bolt for the *American Geophysical Union* (*Bolt*, 2002).

A Web site has been established where photographs, press releases, and testimonials are available at `http://www.seismo.berkeley.edu/seismo/news/tom_mcevilly.html`.

# 2.   McEvilly Graduate Student Fellowship in Seismology

To preserve his memory, Tom's family has requested that the Department of Earth and Planetary Science establish the McEvilly Graduate Student Fellowship in Seismology. Contributions toward the McEvilly Graduate Student Fellowship should be made out to "The Regents of the University of California" and addressed to Susan Torrano, Department of Earth and Planetary Science, 307 McCone Hall, University of California, Berkeley, CA, 94720-4767.

# 3.   A   Celebration   Of   Tom McEvilly's Life

Tom's contributions to the BSL, the Department, to seismology, and to his friends and family were celebrated in a memorial service at UC Berkeley on April 22 in the Faculty Club. Ian Carmichael, Barbara Romanowicz, Ernie Majer, Jim Hannon, and Steve McEvilly offered remembrances during the ceremony. Many members of the community shared stories and memories.

The following is a transcript of the address given by Barbara Romanowicz during the service.

## 3.1   Tom McEvilly's career as a seismologist

It is rather hard to summarize in a few minutes Tom's lifetime contributions to Seismology, especially as I was only entering high school and had no clue that there was such a field as Seismology, when Tom was joining the ranks of Ph.D.'s at St Louis University.

So, I decided to give it a personal perspective, and I would like his numerous students and collaborators who are here today to excuse me if I omit some important aspect of Tom's work.

I first became aware of Tom's scientific existence around 1981-82, when, as a post-doc, I was studying surface wave dispersion across Tibet, to remotely unravel the crust and lithospheric structure of that unique area of the world. Tom's early work, indeed his Ph.D. topic, was on the study of crustal structure through the inversion of Love and Rayleigh wave phase velocities under the central US. In this work, which he published in BSSA at the end of 1964, he found that, in this region, he couldn't fit Love and Rayleigh waves with a unique model, implying the existence of anisotropy in the upper mantle under the continent. Well, these were the pioneering days of such studies, but they remain quite current even as I speak. For me this was particularly striking at the time (that is in the early 1980's), as, for whatever it is worth now, I was able to find a single model to fit Love and Rayleigh wave dispersion data across Tibet.

After he came to Berkeley, Tom's work naturally turned to the regional earthquake problem, progressively adding and I will say lots more about that, but since I mentioned my work on Tibet, published in 1982 - it turns out Tom also got interested in Tibet structure as seen by surface waves at about the same time as I did, and with student Kin-Yip Chun proposed, in addition to the very unusual 70 km thick crust, the existence of a mid-crustal low velocity zone in Tibet, an intriguing result from the point of view of rheology and dynamics. Because this work was done in parallel with mine, and I was in France at that time, somehow I only became aware of it much later on, when I came to work at Berkeley.

I first met Tom in person when he became the first president of the IRIS Consortium in 1984. I may have met him earlier, but that's the time I really first paid attention. I still remember having been struck by his cheerful style presiding the IRIS meeting at the Fall San Francisco AGU that year.

So, anyway, back to Tom's career at UC Berkeley since the mid-60's. Several main themes prevail: an interest in seismic instrumentation, which dates back to his involvement with the seismic instrument manufacturer Spregnether, amplified by his participation in regional network issues at the Berkeley Seismographic Station. Tom turned into one of the best experts in seismic instrumentation in the country - in 1982, as a member of

the NAS Committee on Seismology, he chaired an NRC panel and report on seismic networks which resulted in his involvement in the IRIS program from its very beginning. I emphasize this here, because circumstances have it that almost 20 years later, we are holding today and tomorrow, a session of the Executive Committee of IRIS here at Berkeley, and I have asked Dave Simpson, the IRIS president, to later comment specifically on Tom's contribution through IRIS to the seismological community.

For those of you who are not familiar with this program, IRIS stands for Incorporated Research Institutions for Seismology, and is an NSF funded consortium devoted to the development of infrastructure for seismology. Its main 3 components are the Global Seismic Network, a network of 120 seismic stations distributed globally contributing data for the study of the deep structure of the Earth at the global scale, the PASSCAL program, a pool of portable seismic instruments for regional deployments, and a Data Management System to collect, archive and distribute the IRIS data.

The second theme of Tom's research career, has to do with various aspects of applied seismology: involvement in CTBT related research, monitoring of the Geysers geothermal area, and various other studies which he conducted in collaboration with colleagues at Lawrence Berkeley National Laboratory. I will let Ernie Majer comment on those contributions.

The third theme, and one on which I would like to now expand on, is the study of earthquake processes based on observations on the San Andreas system in California. It doesn't take much to figure out that this main direction of Tom's research was profoundly influenced by the 1966 Parkfield earthquake, which occurred shortly after Tom first came to Berkeley. Parkfield is a very small town (population about 20-some the last time I checked) about half way between San Francisco and Los Angeles, on the San Andreas Fault, which has become the focus of intense seismological interest after this 1966 earthquake, because it appeared to be the site of periodically recurring earthquakes of about magnitude 6, every 22 years on average, the 1966 being the last one of a series of 5 documented events. Parkfield also lies right at the boundary between a "locked zone" on the SAF, to the south, which last broke in the 1857 great Los Angeles (Fort Tejon) earthquake, and a "creeping zone" to the north, which slips steadily and may not have ever experienced a large earthquake.

Shortly after 1968, with students Bill Bakun and John Filson, Tom studied the 1966 Parkfield sequence, using surface wave data, which he was an expert on and later went on to study earthquake source processes with a variety of techniques, in particular near field recordings in the 1980's with Keith McLaughlin and Lane Johnson.

Perhaps more significantly, Tom was involved from the very beginning in the Parkfield earthquake prediction experiment which got off the ground in the early 1970's. Notable early contributions are a paper with Lane Johnson in Science in 1973 on the "dilatancy" issue (the change in the ratio of shear to compressional velocities before earthquakes), and his work using the synthetic VIBROSEIS source of shear wave vibrations, with which he produced a large dataset of consistent waveforms to study temporal changes in crustal properties in the vicinity of the San Andreas Fault, as they might relate to earthquakes - a topic which is still generating publications, most recently with Valeri Korneev at LBL and Eleni Karageorgi, now back in Greece. Tom also was an important mover in several other data acquisition programs using artificial sources to study crustal structure, such as CALCRUST in the 1980's, and more recently the BASIX experiment (1993) in the San Francisco Bay Area.

The real highlight of his career, however, emerged from his investment in the deployment of a then highly unique 10 station borehole seismic network at Parkfield, which started producing data in 1987. The idea was to install seismometers several hundred meters under the Earth's surface, to get away from the noise-generating near-surface weathered layers of rocks, and pick-up clear signals from tiny microearthquakes (down to magnitude M -1) that illuminate the fault zone and might reveal something on how the fault works at the microscopic scale. This proved worthwhile. The strong heterogeneity of structure in and around the fault zone turned out to be an issue: it blurred the view and preventing the earthquakes from being accurately located. With students Alberto Michelini and Bill Foxall, Tom first concentrated on resolving this complex structure through joint hypocentral and velocity inversions, unravelling strikingly organized heterogenity in the fault zone. The discovery of repeating earthquakes, clusters of tightly localized tiny earthquakes producing identical seismic waveforms and their systematic exploitation, through the development of an appropriate data mining methodology, with Bill Foxall and then graduate student Bob Nadeau, led to a series of papers of fundamental significance for earthquake physics. Based on 10 years of data from the borehole Parkfield network, Nadeau and McEvilly documented the quasi-periodic occurrence of micro-earthquakes within well identified clusters, and more recently showed the passage of a stress wave across the Parkfield area in the time period 1988-1995. As shown by Nadeau and Johnson (1998), the characteristics of the micro earthquake clusters has consequences on the distribution of strength and stress, as well as heat generation on the fault. Tom's illness caught him in the middle of finalizing most recent work, in which Nadeau and he documented intriguing pulses in slip rate on the San Andreas fault over distances of tens of kilometers.

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To the very end, Tom kept a hands-on approach and wanted to have a chance to "look" at data and process them himself. Bob Nadeau specially travelled to Saint Louis to bring him his Sun workstation so he could work whenever he felt better. It is really too bad that Tom won't be around to glean all the fruits of his hard work at Parkfield, which are only starting to ripen.

Let me finally mention that the Parkfield borehole network has played and is still playing a critical role in the definition of the SAFOD experiment, the San Andreas Fault Observatory at Depth, which is part of the NSF Earthscope Major Research Equipment initiatives hopefully soon to be funded. Tom played a very active role in SAFOD and his absence will be felt.

Closer to home, I would like to finish on a more personal note: Tom's visits (he travelled a lot in recent years) were always like a ray of sunshine at the Berkeley Seismological Laboratory. He was very supportive of our efforts, and I particularly appreciated his advice on delicate diplomatic issues - with him, there was always an easy way out, he had the charm to always turn a confrontational issue into an easy solution - even though he would drive Eleanor, our MSO, crazy with his imaginative solutions to bureaucratic problems - I have lost one of a handful of friends that I could always rely on in my professional life.

# 4.   References

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Bolt, B., Thomas Vincent McEvilly, *EOS, Trans.* *AGU, 83.* 311, 2002.

# Part II
# Operations

# Chapter 3

# California Integrated Seismic Network

## 1. Introduction

Advances in technology have made it possible to integrate separate earthquake monitoring networks into a single seismic system as well as to unify earthquake monitoring instrumentation. In California, this effort was initiated under the TriNet Project in southern California, where Caltech, the then California Division of Mines and Geology, and the USGS combined their efforts to create a unified seismic system for southern California. With major funding provided by FEMA, OES, and the USGS, the TriNet project provided the opportunity to upgrade and expand the monitoring infrastructure, combining resources in federal, state, university partnership. More recently, the California Geological Survey, Caltech Seismological Laboratory, Berkeley Seismological Laboratory, USGS Menlo Park, and the USGS Pasadena have agreed to cooperate on a statewide basis, because of the obvious benefit to the state.

In the 2000-2001 Annual Report, we described the efforts to create this collaboration through the establishment of a memorandum of agreement and the development of the CISN strategic and implementation plans. In the last year, efforts to form the California Integrated Seismic Network (CISN) took a great leap forward.

## 2. CISN Background

### 2.1 Organization

The core CISN institutions (California Geological Survey, Berkeley Seismological Laboratory, Caltech, USGS Menlo Park, USGS Pasadena) and OES have signed a MOA (included in the 2000-2001 Annual Report) that describes the CISN organizational goals, products, management, and responsibilities of member organizations. To facilitate coordination of activities among institutions, the CISN has formed three management centers:

- Southern California Management Center: Caltech/USGS Pasadena

- Northern California Management Center: UC Berkeley/USGS Menlo Park

- Engineering Management Center: California Geological Survey/USGS National Strong Motion Program

A goal of the CISN is for the Northern and Southern California Management Centers operate as twin earthquake processing centers. The Engineering Management Center has the lead responsibility for producing engineering data products.

The Steering Committee oversees CISN projects and is comprised of two representatives from each core institution and a representative from OES. Barbara Romanowicz was elected the first chair of the Steering Committee, and was succeeded in December 2001 by Lucy Jones of USGS Pasadena.

An external Advisory Committee, representing the interests of structural engineers, seismologists, emergency managers, industry, government, and utilities, has been formed for review and oversight. The Advisory Committee is chaired by Bruce Clark of the California Seismic Safety Commission. The Advisory Committee has held meetings in July 2001 and 2002.

The Steering Committee has formed other committees, including a Program Mangement Group to address planning and coordination, a Strong Motion Working Group to focus on issues related to strong-motion data, and a Standards Committee to resolve technical design and implementation issues.

In addition to the core members, several organizations contribute data that enhances the capabilities of the CISN. Contributing members of the CISN include: University of California, Santa Barbara; University of California, San Diego; University of Nevada, Reno; University of Washington; California Department of Water Resources; Lawrence Livermore National Lab; and Pacific Gas and Electric.

### 2.2 CISN and ANSS

The Advanced National Seismic System (ANSS) is being developed along a regionalized model. 8 regions have been organized and the CISN represents the "California

region". Over the last 3 years, ANSS funding in California has primarily been directed to the USGS Menlo Park to expand the strong-motion instrumentation in the San Francisco Bay Area. As a result, instruments at over 100 sites have been installed or upgraded, significantly improving the data available for ShakeMaps.

The CISN is currently developing plans for the FY 02-03 ANSS program.

## 2.3 CISN and OES

The California Governor's Office of Emergency Services has had a long-term interest in coordinated earthquake monitoring. The historical separation between northern and southern California and between strong-motion and weak-motion networks resulted in a complicated situation for earthquake response.

OES has been an advocate of increased coordination and collaboration in California earthquake monitoring and encouraged the development of the CISN Strategic and Implementation Plans. In FY 2001/2002, Governor Gray Davis requested support for the CISN, to be administered through OES. Funding for the California Geological Survey, Caltech and UC Berkeley was made available in spring 2002, officially launching the statewide coordination efforts.

The CISN/OES program was publically announced on April 15, 2002, during a press conference held at the new headquarters of OES in Sacramento. Invited speakers included Dallas Jones, Director of OES; Darryl Young, Director of the Department of Conservation; Jim Davis, California State Geologist; and Lind Gee from the BSL.

# 3. 2001-2002 Activities

The CISN funding from OES facilitated a number of activities at the BSL during the past year.

## 3.1 Expanded Instrumentation

As part of the CISN/OES project, the BSL purchased equipment for 5 BDSN stations, including STS-2 seismometers, Episensors, and Q4120 data loggers. During 2001-2002, BSL staff initiated efforts to identify potential sites, considering such factors as the current distribution of stations, private versus public property, location of power and telecommunications, and geologic materials.

Two new sites north of the San Francisco Bay were located and permitted for development as broadband observatories. In Lake County, the BSL will build an observatory on the property of the Homestake Mining Company's McLaughlin Mine. Further north, the BSL will build an observatory at the Alder Springs Conservation Camp in the Mendocino National Forest. The status of permitting and site preparation is more fully described in Chapter 4.

Other areas under consideration for future installations include the Pt. Reyes area, the Santa Cruz Mountains (in collaboration with UC Santa Cruz), Pacheco Peak (in collaboration with the California Division of Forestry), Hat Creek (in collaboration with UC Berkeley Department of Astronomy), and Carmel Valley (UC Berkeley Hastings Preserve).

## 3.2 Network Operations and Maintenance

As part of the CISN project, the BSL purchased a number of upgrade kits for their Q4120 data loggers with the goal of improving remote diagnostic capabilities. Three different kits were purchased – power board only, calibration board only, and combined power and calibration boards – in order to ensure that every Q4120 has a power board and that every 8-channel Q4120 also has a calibration board. The power boards provide the capability to monitor battery voltage, allowing staff to discriminate between power and telemetry problems remotely. The calibration boards provide the capability to monitor mass position as well as allow remote calibration of the seismic sensors. Both boards also record data logger temperature.

The boards have not yet been received at the BSL. Prior to widespread upgrades, BSL staff will need to establish procedures for installing and testing these upgrades and then develop a plan for systematic deployment. One of the advantages of this upgrade is that the 21 Q4120 8-channel data loggers maintained by the BSL will be fully interchangeable, as will the 9 4-channel systems. This ability to swap data loggers will facilitate maintenance in the future.

## 3.3 Statewide Communications

One of the major accomplishments of the past year was the design and initial implementation of a CISN communications infrastructure. Doug Neuhauser of the BSL took the lead in investigating options and the CISN partners decided to establish a "ring" of T1 communication links (Figure 3.1) with dual routers at each node. As of June 30, 3 of the 5 links have been ordered and installed (2 of which were ordered by the BSL). Caltech placed the orders for the remaining 2 links in July and installation is expected in September. Orders were also placed for 8 of the 10 routers needed to connect the CISN centers, as the BSL agreed to purchase the routers for the USGS Menlo Park, OES, and CGS, in addition to their own. Caltech's order for 2 routers were placed after July 1 - and delivery is expected in September.

When fully implemented, the CISN ring will have full T1 capacity between adjacent nodes with rapid falloever to secure Internet tunnels among the sites. The network will be able to survive the loss of a single node, T1 cir-

**CISN Centers**

Engineering Data Management Center
CGS and USGS NSMP

Office of Emergency Services

Northern California Management Center
UC Berkeley and USGS Menlo Park

Installed link
Order in progress

km
0   50   100

Southern California Management Center
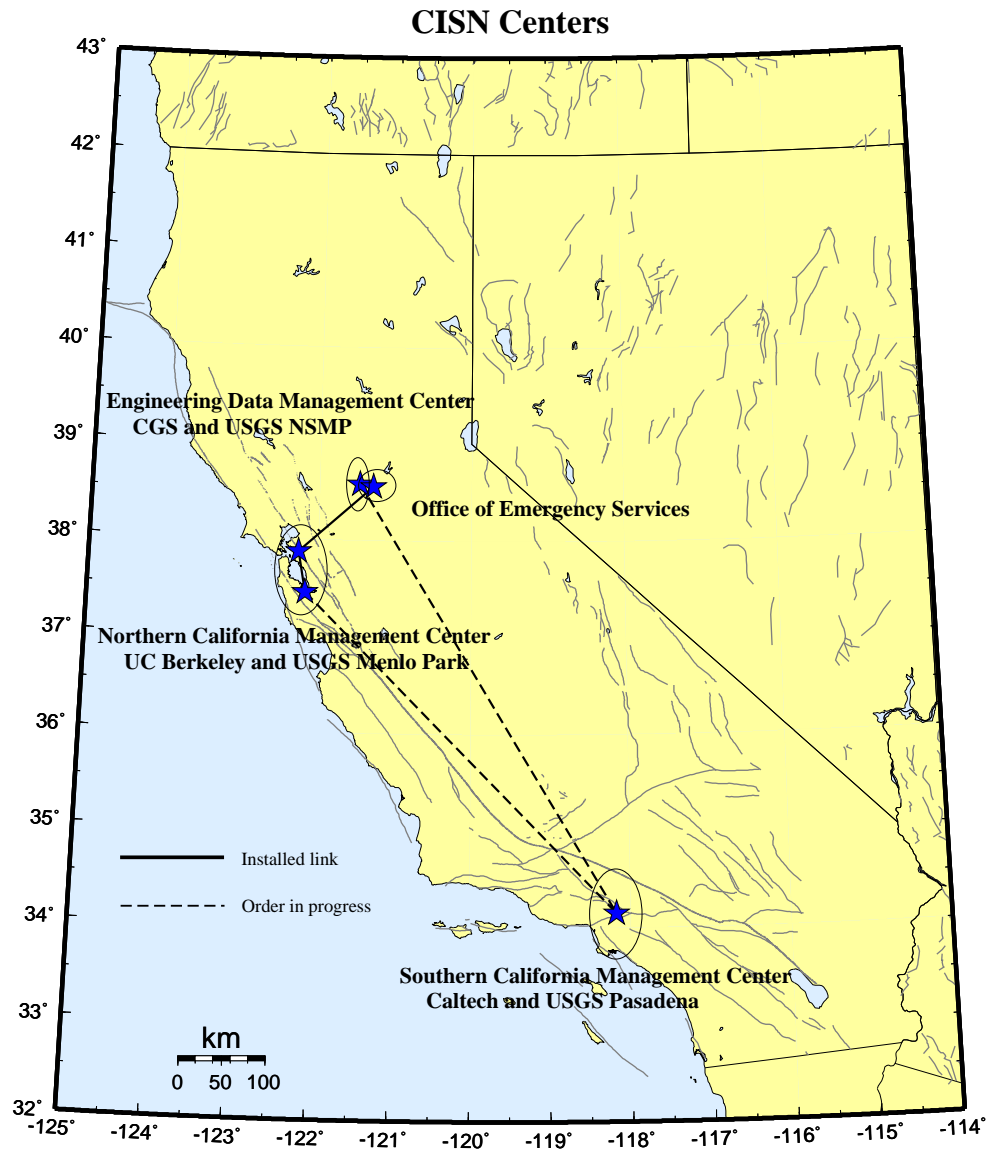Caltech and USGS Pasadena

Figure 3.1: Map showing the geographical distribution of the CISN partners and centers. The communications "ring" is shown schematically with installed links (solid lines) and ordered links (dotted lines).

cuits, or router at any site. The routers will be configured to gracefully fail if one or both links at a node fail.

## 3.4 Northern California Management Center

As part of this effort within the CISN, the BSL and the USGS Menlo Park have begun to plan for the next generation of the northern California joint notification system. Chapter 12 describes the operations of the existing Management Center and reports on design discussions.

### Communications Infrastructure

In order to migrate to a design such as Figure 12.5, the BSL and the USGS Menlo Park need to enhance the communications infrastructure between their sites. Presently, data and information are shared on a dedicated frame-relay connection, with fallback to the Internet.

With OES funding, the BSL commissioned Telecommunications Design Services, Inc. to perform a feasibility study for a microwave communication link between Berkeley and Menlo Park. This study was conducted in June 2002 and a report delivered to the BSL, with copies given to the USGS Menlo Park.

The goal of the study was to evaluate options for a microwave communication link between the BSL and USGS elements of the Northern California Management Center. The report concludes that a repeater site will be required, given the length of the path and the obstructions (buildings, bridges, etc.). According to the report, the Space Sciences Laboratory at UC Berkeley will be a good site for the repeater.

The results of this study are under discussion between the BSL and the USGS. Further discussion is required before moving forward with issues of permission and purchase of hardware.

### Computing Upgrade

The current data acquisition and processing computers used as part of the Northern California Management Center at the BSL are nearly 4 years old. As part of the OES project, the BSL purchased computers to replace these aging systems.

The BSL purchased five Sun 280R computers. Two of these will be used to immediately replace the current data acquisition and processing computers. One will be used to establish a second ShakeMap installation for northern California. (We currently have a "development" installation of ShakeMap operating at the BSL, which uses input from the finite-fault processing to predict ground motions in areas without stations. The new ShakeMap installation will completely parallel the installation in Menlo Park for redundancy.) The remaining two new computers will be used to set up a pilot system for statewide earthquake processing. In addition to the 280R computers, the BSL purchased two Sun StorEdge RAID disk systems. The additional disk systems are required by the expanded waveform exchange among the centers.

The new computer systems were delivered on June 30th. The systems will be deployed in racks in the BSL computer server room and will be configured during the next quarter.

## 3.5 Statewide Integration

In January, the BSL hosted a meeting of the CISN Standards Committee. This meeting was focused on issues related to establishing a statewide earthquake processing system. The Standards Committee defined and prioritized projects necessary to develop a prototype system and established working groups to address them (see the minutes from the meeting at `http://www.cisn.org/standards/meetings.html`).

The working groups include members from all CISN insitutions. Since the January meeting, the Standards Committee has held conference calls approximately every 2-4 weeks to review progress on these issues. The CISN Standards Committee plans to have meetings at least twice a year.

## 3.6 Software Calibration

The CISN partners are working together on the problem of software calibration, particularly as it pertains to automated earthquake processing. Currently, the software implemented in the Southern California Management Center is very different from the software implemented in the Northern California Management Center. Eventually, there may be standardization of software across the management centers, but in the short term, the focus is on calibrating the software to produce the same answers, given the same input data.

In the last year, effort was focused on phase pickers, the association algorithm (binder), the location algorithm (hypoinverse), and magnitude estimation (various). The USGS Menlo Park has taken the lead in testing configurations for a statewide version of the associator and for developing a version of hypoinverse that accounts for velocity models statewide.

The BSL has implemented the Earthworm picker, which is used at Caltech and the USGS Menlo Park, on the data from the Berkeley Digital Seismic Network. All three CISN centers are now running the same picking algorithm, although small differences in configuration exist. We spent some time experimenting with a configuration suitable for its broadband network, as the preliminary configuration produced very few picks. Additional effort is needed to improve the performance of the picker with broadband data.

A test of the association algorithm is underway at the USGS Menlo Park. A preliminary assessment showed

that the Northern and Southern California centers use slightly different configurations of the associator and that these different configurations produce different results. A prototype statewide configuration has been developed and is being tested in Menlo Park and Pasadena.

Staff at the USGS Menlo Park are also working to establish a configuration of the location program for a statewide system. This problem is better defined, as the program can be structured to use different velocity models and station delays.

On the magnitude front, issues of calibration have been complicated by differences between the northern and southern California networks. In southern California, the TriNet upgrade has created a mostly digital seismic network. In northern California, the networks are dominated by analog instrumentation. This means that different magnitude methods are used by each center. A Standards Committee Working Group was tasked to look at the issues presented by this different in infrastructure.

As part of this effort, the BSL has been looking at some of the software developed under the TriNet project with the goal of adapting it for northern California. Of particular interest are the codes which continuously process waveform data to create timeseries of pre-computed amplitudes (*Kanamori et al.*, 1999) such as Ml100 (local magnitude computed for a fixed distance of 100 km), Me100 (energy magnitude computed for a fixed distance of 100 km), peak ground acceleration, peak ground velocity, and spectral acceleration at 3, 1, and 0.3 seconds. The continuous processing of the amplitudes is advantageous in providing a steady computing load (as opposed to "peaking" during an earthquake) and rapid access to the data of interest.

Caltech has shared this software with the BSL. Unfortunately, the package could not be installed "as is" and modifications were required. In particular, changes were required to support network and location codes (the SNCL problem). Considerable time was spent in tracking timing discrepancies between the TriNet software and BSL codes for handling waveforms and a small bug in the TriNet codes was found.

As of June 30th, the BSL has adapted versions of the programs which place waveform data in a "common data area (cda)", extract data from the cda, process waveform data to produce reduced amplitude timeseries and write them an "amplitude data area (ada)", and read amplitudes from the ada.

The BSL plans to bring up these codes on the Sun Fire 280r computers as soon as the new computers are configured. This will allow the Northern and Southern California Management Centers to begin exchanging the reduced amplitude time series.

Beyond establishing the amplitude exchange between the centers, the next step for the NC center to modify the existing software to make use of these pre-computed amplitudes. This requires changes to several modules in the REDI system. BSL staff are considering several possible approaches. This aspect of the implementation is complicated by the fact that the original TriNet programs use commercial software to perform some functions.

Once the software is operational within the REDI system, the question of magnitude corrections will need to be addressed. Historically, Caltech and the BSL have held different views about the calibration of Wood-Anderson seismometers. As a result, the amplitudes computed from the TriNet software uses a different gain than that used in equivalent BSL processing. This difference will merit careful review in order to avoid introducing problems with the historical catalog.

## 3.7 Data Exchange

Pick exchange was initiated between the Northern and Southern California Management Centers during the previous quarter. With the implementation of the Earthworm picker at the BSL, picks from the BSL have been added to those from the USGS Menlo Park and Caltech.

In the spring, a CISN Standards WG proposed a model for exchanging the reduced amplitude timeseries. During this quarter, BSL staff developed software to use this model for exchange: ada2ring (which reads the amplitudes from an ada and writes them to an Earthworm ring) and ring2ada (which reads the amplitudes from an Earthworm ring and writes them to an ada. These programs will allow the CISN to begin exchanging the pre-computed amplitudes using existing Earthworm import/export software. The software developed at the BSL has been tested locally, and a copy given to Caltech so that the center-center feed may be tested. Full exchange will be implemented when the BSL has the new Sun Fire 280r computers configured.

Also during this year, Caltech and the BSL identified 20 stations (10 each) which will be configured to send data to both the Northern and Southern California Data Centers (Figure 3.2). Caltech and the BSL both ordered the DLCIs (data link connection identifier) which will allow the 2nd center to establish a PVC (permanent virtual circuit) to each station using the frame-relay network.

Doug Neuhauser began working on the necessary configuration changes to the Quanterra data loggers. The new Quanterra configuration will allow for 4 telemetry links at each data logger: 1 primary and 1 secondary link to the BSL, 1 link to Caltech, and 1 additional link.

BSL staff participated in a working group to define a new format for exchanging ground motion amplitudes. The purpose of this format is to insure all information necessary for building ShakeMaps and constructing Internet Quick Reports is available.
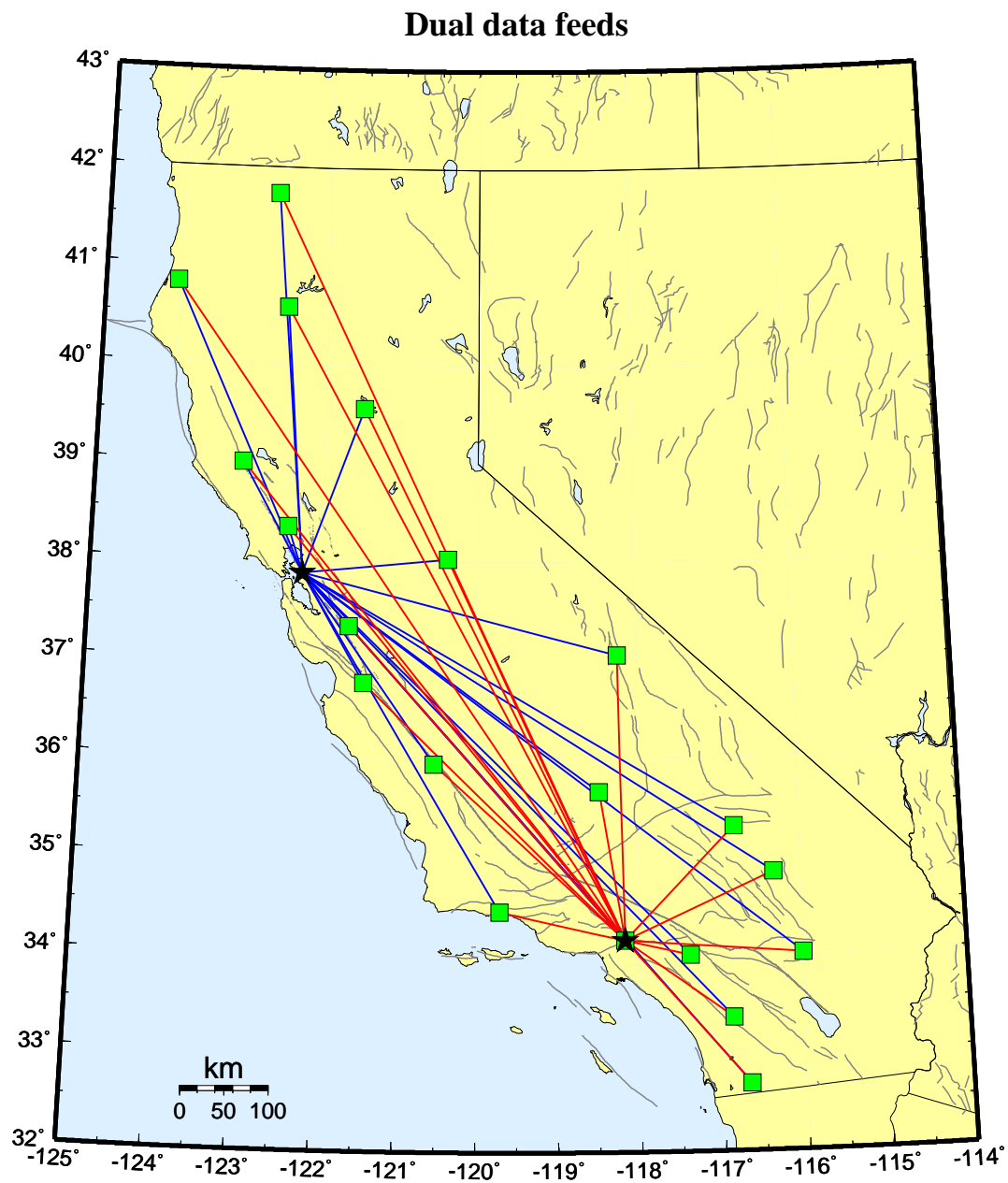
Figure 3.2: Map showing the 20 stations selected to send data directly to the northern and southern California processing centers.

## 3.8 Statewide Earthquake processing

To establish a testbed for statewide processing, several elements must be in place;

- a) full pick exchange

- b) statewide association algorithm

- c) statewide location algorithm

- d) waveform or amplitude time series exchange

- e) standardized magnitude estimation

- f) calibration of station corrections for magnitude

At this point in time (a) is largely complete. Items (b) and (c) are underway. Additional work is required for items (d-f) at this time.

# 4. Acknowledgements

# Chapter 4

# Berkeley Digital Seismic Network

## 1. Introduction

The Berkeley Digital Seismic Network (BDSN) is a regional network of very broadband and strong motion seismic stations spanning northern California and linked to UC Berkeley through continuous telemetry (Figure 4.1 and Table 4.1). This network is designed to monitor regional seismic activity at the magnitude 3+ level as well as to provide high quality data for research projects in regional and global broadband seismology.

The network upgrade and expansion initiated in 1991 has continued, and it has grown from the original 3 broadband stations installed in 1986-87 (BKS, SAO, MHC) to 23 stations in 2002. One station was added in the past year (HUMO).

We take particular pride in high quality installations, which involves often lengthy searches for appropriate sites away from sources of low-frequency noise as well as continuous improvements in installation procedures and careful monitoring of noise conditions at existing stations.

Future expansion of our network is contingent on the availability of funding and coordination with other institutions for the development of a denser state-of-the-art strong motion/broadband seismic network and joint earthquake notification system in this seismically hazardous region.

## 2. BDSN Overview

Twenty-one of the BDSN sites are equipped with 3 component broadband seismometers and strong-motion accelerometers, and a 24-bit digital data acquisition system or data logger. Two additional sites (RFSB and SCCB) consist of a strong-motion accelerometer and a 24-bit digital data logger. Data from all BDSN stations are transmitted to UC Berkeley using continuous telemetry. In order to insure against data loss during utility disruptions, each site has a 3-day supply of battery power and is accessible via a dialup phone line. The combination of high-dynamic range sensors and digital data loggers ensures that the BDSN has the capability to record the full range of earthquake motion for source and structure studies. Table 4.2 lists the instrumentation at each site.

Most BDSN stations have Streckeisen three-component broadband sensors (*Wielandt and Streckeisen*, 1982; *Wielandt and Steim*, 1986). Guralp CMG-3T downhole broadband sensors contributed by LLNL are deployed in post-hole installations at BRIB and FARB. The strong-motion instruments are Kinemetrics FBA-23 or FBA-ES-T with ± 2 g dynamic range. The recording systems at all sites are either Q730, Q680, Q980 or Q4120 Quanterra data loggers, with 3, 6, 8, or 9 channel systems. The Quanterra data loggers employ FIR filters to extract data streams at a variety of sampling rates and these have been implemented as acausal filters in the BDSN. In general, the BDSN stations record continuous data at .01, 0.1, 1.0, and 20.0 samples per second and triggered data at either 80 or 100 samples per second using the Murdock, Hutt, and Halbert event detection algorithm (*Murdock and Hutt*, 1983) (Table 4.3). In addition to the 6-channels of seismic data, signals from thermometers and barometers are recorded at nearly every site (Figure 4.2).

In parallel with the upgrade of the broadband network, a grant from the CalREN (California Research and Education Network) Foundation enabled the BSL to convert data telemetry from analog leased lines to digital frame-relay connections. The frame-relay network uses digital phone circuits that can support 56 Kbit/s to 1.5 Mbit/s throughput. Since frame-relay is a packet-switched network, a site may use a single physical circuit to communicate with multiple remote sites through the use of "permanent virtual circuits". Frame Relay Access Devices (FRADs), which replace modems in a frame-relay network, can simultaneously support multiple interfaces such as RS-232 async ports, synchronous V.35 ports, and ethernet connections. In practical terms, the upgrade to frame relay communication provides faster data telemetry between the remote sites and the BSL, remote console control of the data loggers, additional services such as ftp and telnet to the data loggers, data transmission to multiple sites, and the ability to communicate and transmit
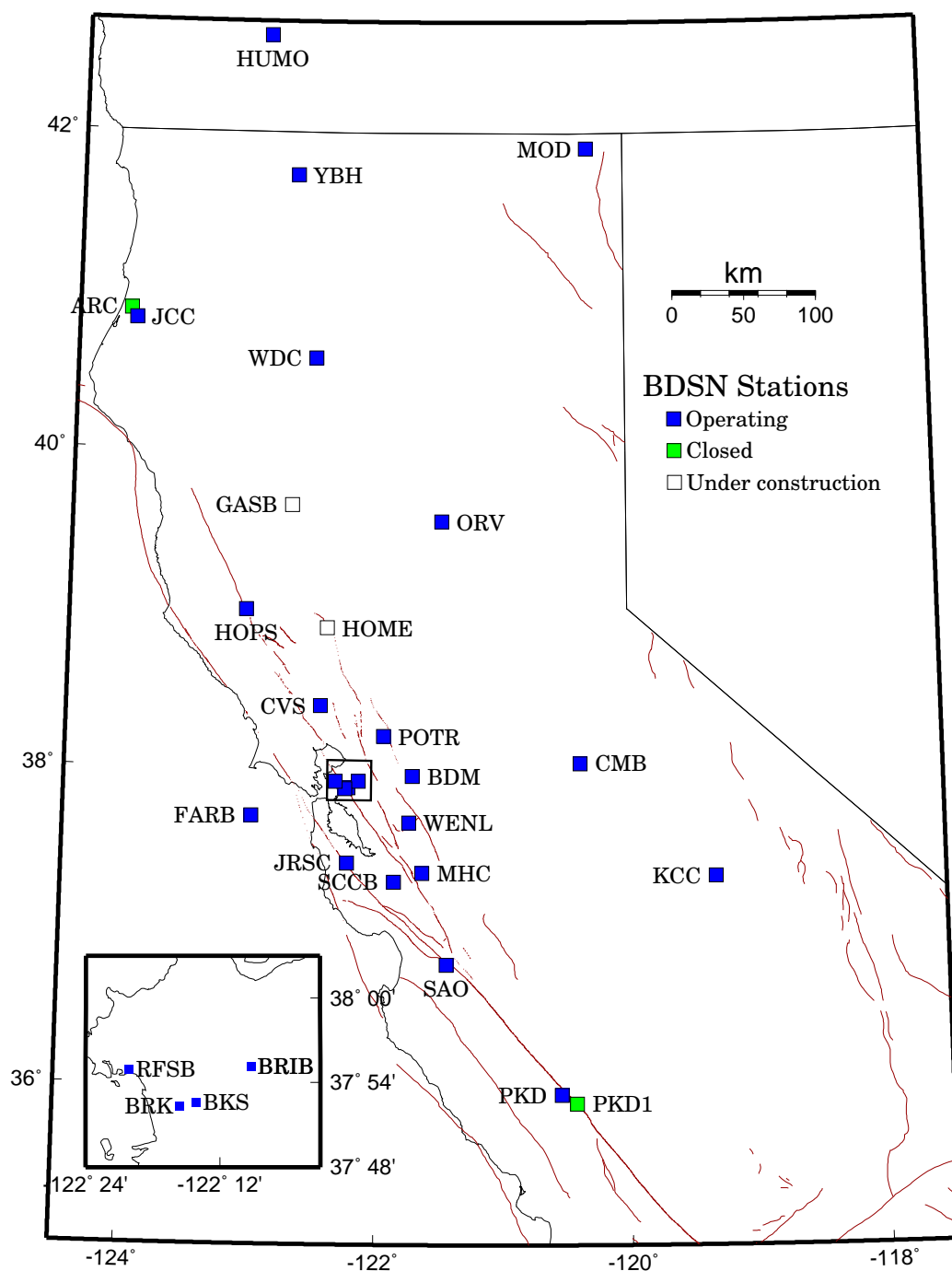
Figure 4.1: Map illustrating the distribution of operational (filled squares), planned (open squares), and closed (grey squares) BDSN stations in northern and central California.
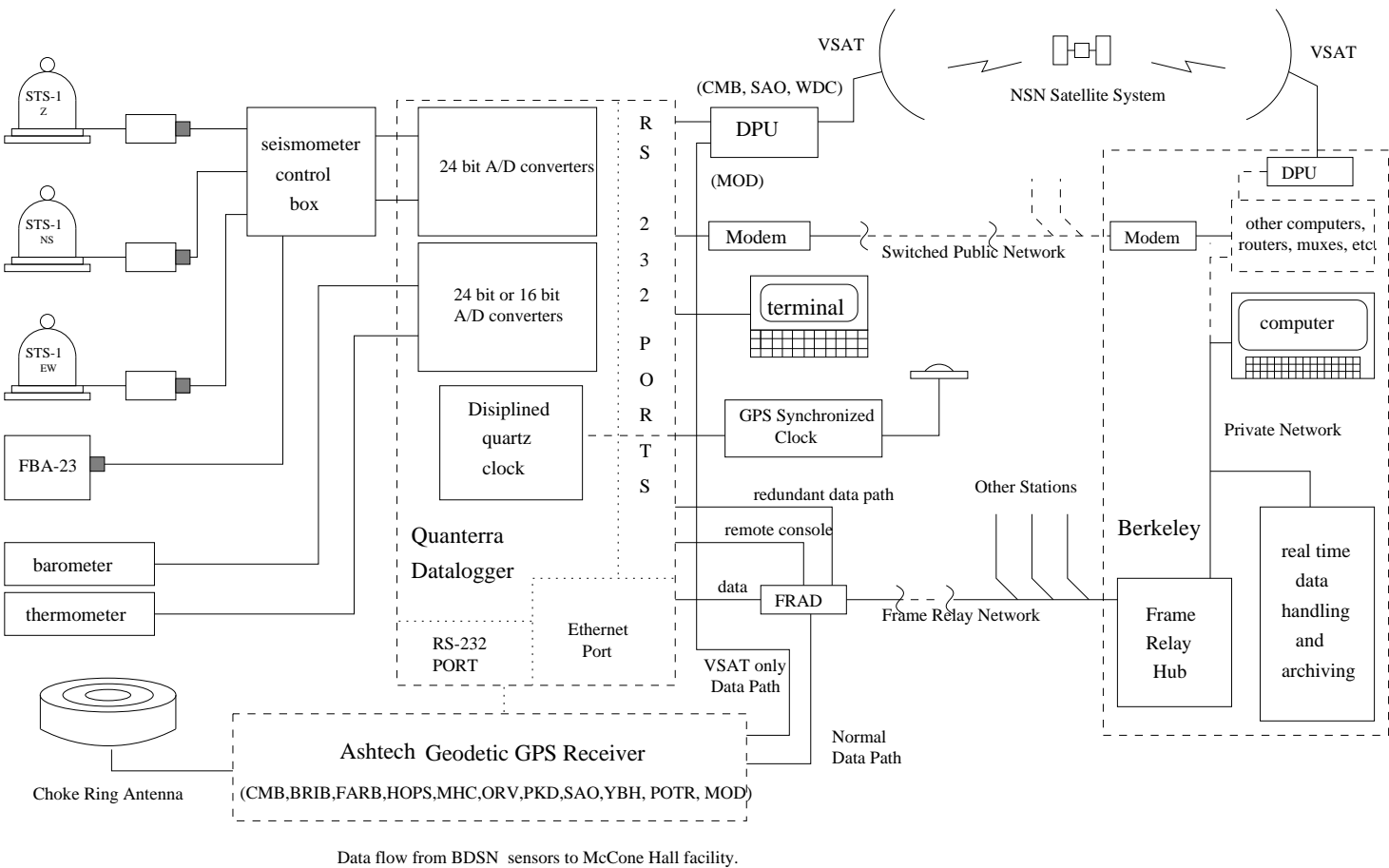
Figure 4.2: Schematic diagram showing the flow of data from the sensors through the data loggers to the central acquisition facilities of the BSL. This particular example shows an STS-1, an FBA-23, thermometer, barometer, and a GPS receiver.

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data from multiple instruments such as GPS receivers and/or multiple data loggers at a single site. Today, 20 of the BDSN sites use frame-relay telemetry for all or part of their communications system.

As described in Chapter 11, data from the BDSN are acquired centrally at the BSL. These data are used in the Rapid Earthquake Data Integration System as well as in routine earthquake analysis (Chapter 12). As part of routine quality control (Chapter 11), power spectral density analyses are performed weekly and Figure 4.3 shows a summary of the results for 2001-2002. The occurrence of a significant teleseism also provides the opportunity to review station health and calibration and Figure 4.4 displays the response of the BDSN to a $M_w$ 7.3 earthquake in Russia-China border region.

BDSN data are archived at the Northern California Earthquake Data Center and this is described in detail in Chapter 13.

| Sensor | Channel | Rate (sps) | Mode | FIR |
|--------|---------|-----------|------|-----|
| Broadband | UH? | 0.01 | C | Ac |
| Broadband | VH? | 0.1 | C | Ac |
| Broadband | LH? | 1.0 | C | Ac |
| Broadband | BH? | 20.0 | C | Ac |
| Broadband | HH? | 80.0/100.0 | T | Ac |
| Strong-motion | LL? | 1.0 | C | Ac |
| Strong-motion | BL? | 20.0 | C | Ac |
| Strong-motion | HL? | 80.0/100.0 | C | Ac |
| Thermometer | LKS | 1.0 | C | Ac |
| Barometer | LDS | 1.0 | C | Ac |

Table 4.3: Typical data streams acquired at BDSN stations, with channel name, sampling rate, sampling mode, and the FIR filter type. C indicates continuous; T triggered; Ac acausal. The LL and BL strong-motion channels are not transmitted over the continuous telemetry but are available on the Quanterra disk system if needed.

# 3. 2001-2002 Activities

## 3.1 Station Maintenance

Given the remoteness of the off-campus stations, BDSN data acquisition equipment and systems have been designed, configured, and installed for both cost effectiveness and reliability. As a result, the need for regular station visits has been reduced. Most station visits are necessitated by some catastrophic failure. The 2001-2002 fiscal year was no exception.

### Vandalism

At station JCC, vandals broke into the steel and concrete vault, cut the instrument power cables, and stole the station batteries. Data acquisition was interrupted
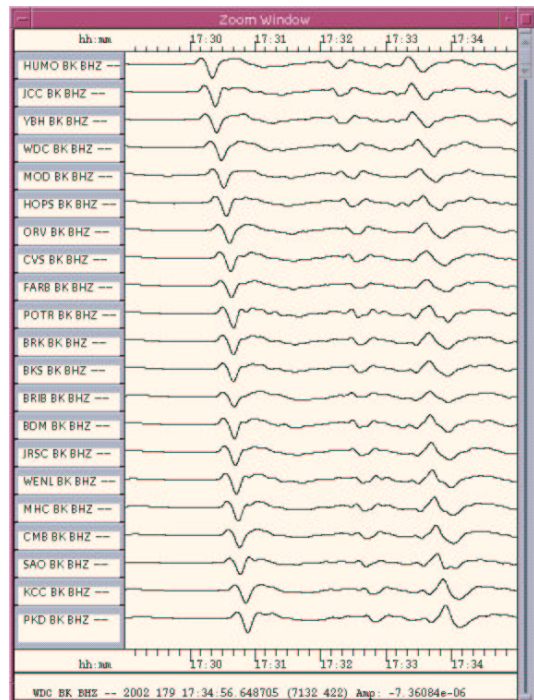


Figure 4.4: BDSN Z-component broadband recording of the P, pP and sP recorded waveforms from a large deep focus teleseism the occurred in the Russia-northeast China border region ($M_w$ 7.3; 2002.179,17:19; depth 566 km; 75 deg NW of Berkeley). The waveforms have been bandpass filtered (0.01-0.1 Hz), deconvolved to absolute ground displacement, and ordered by distance from the epicenter. The similarity of the waveforms in the BDSN broadband records implies that the vertical components are responding normally and that the instrument responses are correct.
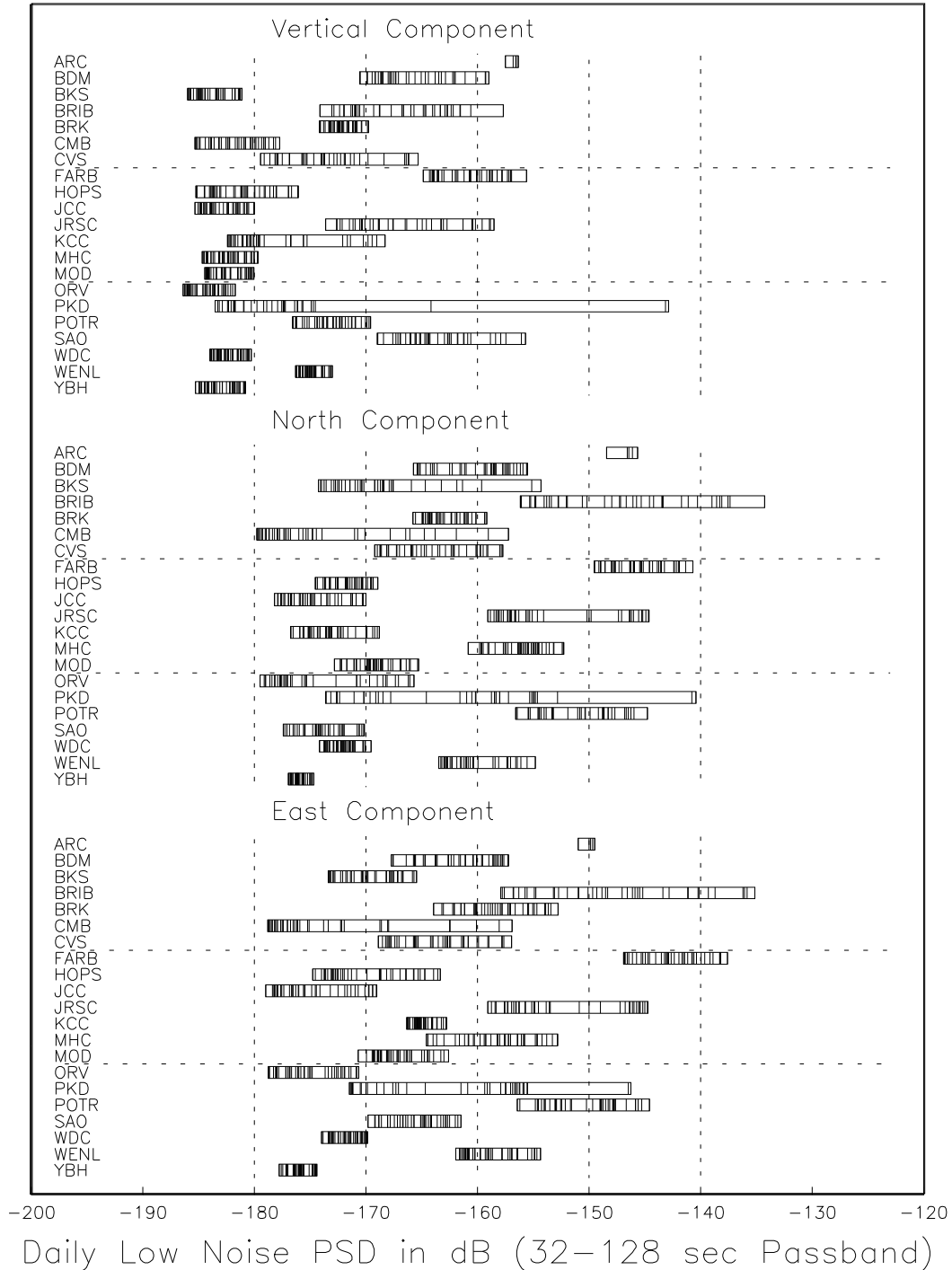
Figure 4.3: PSD noise analysis for BDSN stations, by channel, in the period range from 32-128 sec. PKD stands out in terms of its high noise level variation, which was caused by a problem in the sensor. FARB, sited on the Farallon Islands, stands out as the station with the highest average background noise level. BRIB, sited in a shallow borehole on a hillside prone to seasonal tilting, is also relatively noisy. YBH, sited in a remote and abandoned hard rock mining drift, stands out as exceptionally quiet site. The newest BDSN station, JCC, is also among the quietest of the BDSN stations.

| Code | Net | Latitude | Longitude | Elev (m) | Over (m) | Date | Location |
|------|-----|----------|-----------|----------|----------|------|----------|
| ARC | BK | 40.87772 | -124.07738 | 30.1 | 0 | 1992/05 - 2001/07 | HSU, Arcata |
| BDM | BK | 37.95397 | -121.86554 | 219.8 | 34.7 | 1998/11 - | Black Diamond Mines, Antioch |
| BKS | BK | 37.87622 | -122.23558 | 243.9 | 25.6 | 1988/01 - | Byerly Vault, Berkeley |
| BRIB | BK | 37.91886 | -122.15179 | 219.7 | 2.5 | 1995/06 - | Briones Reservation, Orinda |
| BRK | BK | 37.87352 | -122.26099 | 49.4 | 2.7 | 1994/03 - | Haviland Hall, Berkeley |
| CMB | BK | 38.03455 | -120.38651 | 697.0 | 2 | 1986/10 - | Columbia College, Columbia |
| CVS | BK | 38.34526 | -122.45840 | 295.1 | 23.2 | 1997/10 - | Carmenet Vineyard, Sonoma |
| FARB | BK | 37.69782 | -123.00110 | -18.5 | 0 | 1997/03 - | Farallon Island |
| HOPS | BK | 38.99349 | -123.07234 | 299.1 | 3 | 1994/10 - | Hopland Field Stat., Hopland |
| HUMO | BK | 42.60710 | -122.95669 | 554.9 | TBD | 2002/06 - | Hull Mountain, Oregon |
| JCC | BK | 40.81745 | -124.02955 | 27.2 | 0 | 2001/04 - | Jacoby Creek |
| JRSC | BK | 37.40373 | -122.23868 | 70.5 | 0 | 1994/07 - | Jasper Ridge, Stanford |
| KCC | BK | 37.32363 | -119.31870 | 888.1 | 87.3 | 1995/11 - | Kaiser Creek |
| MHC | BK | 37.34164 | -121.64257 | 1250.4 | 0 | 1987/10 - | Lick Obs., Mt. Hamilton |
| MOD | BK | 41.90246 | -120.30295 | 1554.5 | 5 | 1999/10 - | Modoc Plateau |
| ORV | BK | 39.55451 | -121.50036 | 334.7 | 0 | 1992/07 - | Oroville |
| PKD | BK | 35.94517 | -120.54160 | 583.0 | 3 | 1996/08 - | Bear Valley Ranch, Parkfield |
| PKD1 | BK | 35.88940 | -120.42611 | 431.6 | 0 | 1991/10 - 2000/09 | Haliburton House, Parkfield |
| POTR | BK | 38.20263 | -121.93535 | 20.0 | 6.5 | 1998/02 - | Potrero Hill, Fairfield |
| RFSB | BK | 37.91608 | -122.33607 | -26.7 | 0 | 2001/02 - | RFS, Richmond |
| SAO | BK | 36.76403 | -121.44722 | 317.2 | 3 | 1988/01 - | San Andreas Obs., Hollister |
| SCCB | BK | 37.28773 | -121.86584 | 101.6 | 0 | 2000/04 - | SCC Comm., Santa Clara |
| WDC | BK | 40.57988 | -122.54113 | 268.3 | 75 | 1992/07 - | Whiskeytown |
| WENL | BK | 37.62211 | -121.75697 | 138.9 | 30.3 | 1997/06 - | Wente Vineyards, Livermore |
| YBH | BK | 41.73204 | -122.71039 | 1059.7 | 60.4 | 1993/07 - | Yreka Blue Horn Mine, Yreka |

Table 4.1: Stations of the Berkeley Digital Seismic Network. Each BDSN station is listed with its station code, network id, location, operational dates, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame and the elevation (in meters) is relative to the WGS84 reference ellipsoid. The elevation is either the elevation of the pier (for stations sited on the surface or in mining drifts) or the elevation of the well head (for stations sited in boreholes). The overburden is given in meters. The date indicates either the upgrade or installation time.

while the batteries were replaced and multiple steel locking mechanisms were installed to prevent future vandalism. Local police were notified.

Local police were also notified when vandals broke into the instrument enclosure and stole the GPS receiver at SAO. Engineers from the BSL rebuilt the enclosure building and instrument mounting in a manner to minimize the likelihood of future problems, although the proximity of this site to areas of public access remains a concern.

**BDM Power system**

We experienced problems at BDM (Black Diamond Mine) this year, with the data logger and telemetry subsystem rebooting periodically. The cause of the reboots was found to be the interaction among a power supply of marginal size, a low voltage cut-off device, and battery with an internally shorted cell. When the line power to the data acquisition system was turned off, the system batteries would power the system until the battery voltage was sufficiently reduced to cause the low voltage

device to turn off all power to the system. When the line power was restored, the power supply was inadequately sized to raise the voltage of the internally shorted battery high enough that the system could reboot while pulling the battery voltage lower to the point of the low voltage device turning the system off again. The cycle would thus repeat indefinitely. BSL engineers replaced all the station batteries and installed a larger power supply.

**PKD**

At station PKD, data are telemetered via spread spectrum radios from the vault to Carr Hill, where a frame-relay connection carries the data to Berkeley. During the past year, as additional groups have added experiments and additional radios, the radio throughput became unacceptably low. After multiple trips and collaboration with USGS and other technicians, BSL engineers were able to improve the data rate by raising the height of the antenna and changing polarization of the transceiver antennas. However, data throughput could diminish fur-

| Code | Broadband | Strong-motion | Data logger | T/B | GPS | Other | Telemetry | Dial-up link |
|------|-----------|---------------|-------------|-----|-----|-------|-----------|--------------|
| ARC | STS-2 | FBA-23 | Q980 | | | | FR | X |
| BDM | STS-2 | FBA-23 | Q4120 | X | | | FR | |
| BKS | STS-1 | FBA-23 | Q980 | X | | Baseplates | FR | X |
| BRIB | CMG-3T | FBA-23 | Q980 | | X | Vol. Strain | FR | X |
| BRK | STS-2 | FBA-23 | Q680 | | | | POTS | |
| CMB | STS-1 | FBA-23 | Q980 | X | X | Baseplates | FR/NSN | X |
| CVS | STS-2 | FBA-23 | Q4120 | X | | | FR | |
| FARB | CMG-3T | FBA-23 | Q4120 | X | X | | R-FR/R | |
| HOPS | STS-1 | FBA-23 | Q980 | X | X | Baseplates | FR | X |
| HUMO | STS-2 | FBA-ES-T | Q4120 | X | | | NSN | X |
| JCC | STS-2 | FBA-23 | Q980 | X | | | FR | X |
| JRSC | STS-2 | FBA-23 | Q680 | | | | FR | X |
| KCC | STS-1 | FBA-23 | Q980 | X | | Baseplates | R-Mi-FR | X |
| MHC | STS-1 | FBA-23 | Q980 | X | X | | FR | X |
| MOD | STS-1 | FBA-ES-T | Q980 | X | X | Baseplates | NSN | X |
| ORV | STS-1 | FBA-23 | Q980 | X | X | Baseplates | FR | X |
| PKD | STS-2 | FBA-23 | Q980 | X | X | EM | R-FR | X |
| PKD1 | | FBA-23 | Q980 | | | | FR | X |
| POTR | STS-2 | FBA-ES-T | Q4120 | X | X | | FR | X |
| RFSB | | FBA-ES-T | Q730 | | | | FR | |
| SAO | STS-1 | FBA-23 | Q980 | X | X | Baseplates, EM | FR/NSN | X |
| SCCB | | FBA-ES-T | Q730 | | X | | FR | |
| WDC | STS-2 | FBA-23 | Q980 | X | | | FR/NSN | X |
| WENL | STS-2 | FBA-23 | Q4120 | X | | | FR | |
| YBH | STS-1 | FBA-23 | Q980 | X | X | Baseplates | FR | X |

Table 4.2: Instrumentation of the BDSN as of 06/30/2002. Every BDSN station consists of collocated broadband and strong-motion sensors, with the exception of PKD1, RFSB and SCCB which are strong-motion only, with a 24-bit Quanterra data logger and GPS timing. Additional columns indicate the installation of a thermometer/barometer package (T/B), collocated GPS receiver as part of the BARD network (GPS), and additional equipment (Other) such as warpless baseplates or electromagnetic sensors (EM). The main and alternate telemetry paths are summarized for each station. FR - frame relay circuit, R - radio, Mi - microwave, POTS - plain old telephone line, NSN - USGS NSN satellite link. An entry like R-Mi-FR indicates multiple telemetry links, in this case, radio to microwave to frame relay.

ther if additional transmitters are added near Parkfield.

Also during 2001-2002, the STS-2 sensor at PKD was replaced. Routine PSD analysis indicated an increase in the noise level.

2003. The STS-2 will be deployed in parallel with the existing STS-1 seismometers, bringing YBH into compliance as an auxillary station of the IMS.

### YBH Upgrades

Station YBH was previously chosen as an alternative monitoring station by both IMS and DTRA. In collaboration with the IMS, BSL installed a VSAT data link, long-period microbaragraph, and separate battery backup. We also installed an IMS-supplied, stand-alone data validation computer and door switch. To observe long periods on the microbargraph, the sensor was installed in a copper pipe anchored to the rock wall of the adit. Foam insulation was applied to the outside of the copper pipe to further dampen the temperature fluctuations of the sensor. Additionally, a second pier was constructed at YBH for installation of an STS-2 seismometer in 2002-

### CMB Trailer

After many years of service, the portable trailer at CMB was retired. This structure housed the data logger and other electronics. Prior to its deployment at CMB, the trailer was in service at the Jamestown station for nearly twenty years. The combination of the structural failure, the pooling of rainwater on the roof, and the collapse of the floor led to the purchase and installation of a steel shipping container in 2001-2002. Special attention was paid to insulating, and grounding the the container prior to installation of the data acquisition and telemetry equipment.

**STS-1 hinges**

In November of 2001, Bob Uhrhammer reported observations of 1-sided steps on the STS-1 North component at station BKS. In January and early February of 2002, BSL staff replaced the electronics box and tested the baseplates, and concluded that rust on the sensor hinge was the source of the noise. Small rust spots were observed on another STS-1 sensor (both sensors had not been evacuated in their early history).

Since replacement hinges are not available from Streckheisen - and since as many as 20 BDSN sensors could develop this problem, BSL staff began efforts to manufacture replacement hinges. During a visit in February, Erhard Wielandt recommended replacing all 4 hinges simultaneously, using material similar to the original. BSL staff spent time developing a reproducible recipe for the hinges, including laser cutting the edges for smoothness. The first set of replacement hinges is being tested now.

## 3.2  New Installations

### Hull Mountain, Oregon (HUMO)

In the fall of 2000, we began a search for a site to extend BDSN north of the California/Oregon border, as part of a collaboration with the USGS National Seismic Network and the Global Seismic Network of IRIS, to be located north of the midpoint between the existing sites at MOD and YBH. This station will be one ofthe sites of the 100 station NSN/GSN "backbone" in the U.S. Our experience shows that sites which are located on hard granite have less ground tilt and are quieter in the long period, so the first step in locating the new site was to consult a geological map of the area.

In the Medford, Oregon area, we contacted officials at six ranger offices within two National Forests, and the Bureau of Land Management in hopes of finding an abandoned mining adit similar to YBH and MOD. This area was historically an active mining region with many possible sites. Several of the possible adit sites were flooded, several more were located but had collapsed since mining ending, and others were deemed too far from utilities. A suitable adit was located north of Medford, 12 kilometers west of Shady Cove, and this site was permitted with the US Bureau of Land Management. By placing the seismographic equipment on public lands as opposed to private lands, the longevity of the site is assured.

Although instruments located underground clearly exhibit better signal to noise characteristics, technical challenges to securing the site, power, telemetry, and external clock present themselves as a result of this type of installation.

As found, the front of the adit was largely blocked by a small landslide. The entrance was excavated and a steel culvert placed to line the weathered rock near the entrance, prevent collapse, and to provide an anchor point for a lockable grate steel grate. Commercial power and phone lines were trenched and placed below the steel culvert. At this location, at the request of the BLM biologist, a solid door was not used in order that bats may enter and hibernate during winter months. All instrumentation -data logger, seismometers, battery back up, barometer, thermistor and telemetry equipment, is located 110 meters inside of the adit. To achieve external GPS clock signal, a high gain antenna was placed outside the adit. Low attenuation coaxial cable connects the antenna and the data logger clock.

At this time, connection to the National Seismic Network VSAT is being established. Because the equipment is underground and the site is located within a mature forest, it was necessary to locate the VSAT dish approximately 300 meters away from the data logger in a location with a view of the southern sky (where the NSN satellite is located). To achieve digital telemetry over this distance, a fiber optic link will connect the data logger with the VSAT hardware. Again, all data and power lines will be trenched and buried.

While the VSAT system is being completed, the station is accessible via a dial-up phone line. Preliminary data analysis indicates that the background noise level at HUMO is lower than that observed at WDC. Figure 4.5 shows raw P waveforms at HUMO and WDC from a recent teleseism.

In this collaborative effort, the USGS/NSN provided the STS-2 seismometer, the BSL supplied the Episensors and the Quanterra data logger, and IRIS provided support for the installation expenses.

## 3.3  New Site Development

In the past year, two new sites north of the San Francisco Bay were located and permitted for development as broadband observatories. In Lake County, the BSL will build an obsevatory on the property of the Homestake Mining Company's McLaughlin Mine. Further north, the BSL will build an observatory at the Alder Springs Conservation Camp in the Mendocino National Forest.

### McLaughlin Mine

The McLaughlin Mine site is on property owned and formerly operated by Homestake Mining Company as a surface gold mine. Although local geological maps indicate the area to be volcanic in origin, the mining operation revealed the geology to be extremely varied and complex. With the conclusion of mining operations, the property will be managed as a UC-Davis reserve for research. The seismographic vault will be one of the first research projects on the new reserve. The site will be located approximately 20 kilometers east of the town of Lower Lake, California. The area where the vault will be constructed consists largely of Franciscan sandstone. At this time, a contractor has been hired to excavate and
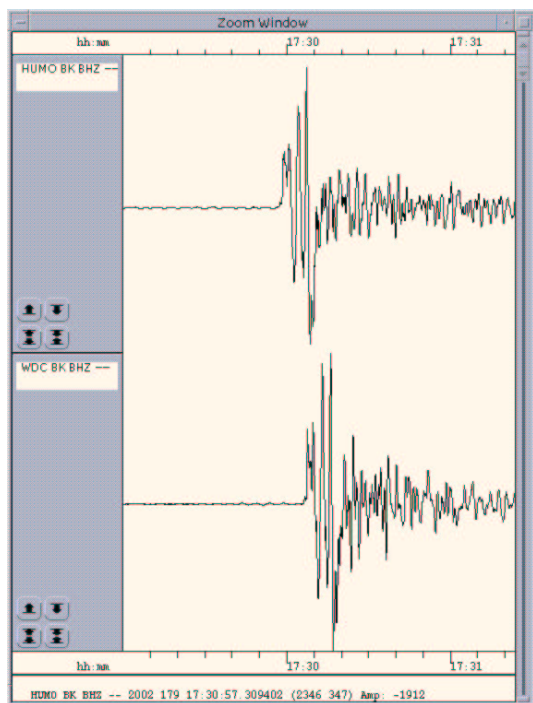
Figure 4.5: A comparison of the raw P-wave Z-component waveform recorded by the STS-2 broadband seismometer sited at the newest BDSN station at Hull Mountain, OR (HUMO) with the corresponding waveform recorded by the STS-2 broadband seismometer sited at Whiskeytown Dam, CA (WDC) 228 km S of HUMO. The P-waves were generated by a large deep-focus teleseism that occurred in the Russia-northeast China border region ($M_w$ 7.3; 2002.179,17:19; depth 566 km; 72 degrees NW of HUMO). Both stations are sited in remote abandoned hard rock mining drifts. The highly similar first ∼15 seconds of the P-wave waveforms shows that the two stations are responding nearly identically to the teleseismic signal and the differences later in the P-wave coda are due primarily to differences in the crustal structure at the two sites.

construct a vault from a steel container similiar to those found at stations JCC, PKD, and HOPS. The BSL has registered the name HOME for this site.

### Alder Springs

Located approximately 35 kilometers west of the central valley town of Williams, at the Alder Springs site a short period observatory is operated by the California Department of Water Resources. Rocks are mostly serpentine in nature. Again, a seismographic vault similar to those at JCC, PKD, and HOPS will be built. The BSL vault will house the Department of Water Resources equipment presently installed in a fiberglass enclosure. This site has been named GASB by the BSL.

## 4.    Acknowledgements

## 5.    References

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Wielandt, E., and G. Streckeisen, The leaf spring seismometer: design and performance, *Bull. Seis. Soc. Am., 72,* 2349-2367, 1982.

# Chapter 5

# Northern Hayward Fault Network

## 1.  Introduction

Complementary to the regional broadband network, a deployment of borehole-installed, wide-dynamic range seismographic stations is being established along the Hayward Fault and throughout the San Francisco Bay toll bridges network. This project is a cooperative development of the BSL and the USGS, with support from USGS, Caltrans, EPRI, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL, and LBNL (Figure 5.1 and Table 5.1).

The purpose of the network is twofold: to lower substantially the threshold of microearthquake detection and increase the recorded bandwidth for events along the Hayward fault; and to obtain bedrock ground motion signals at the bridges from small earthquakes for investigating bridge responses to stronger ground motions. A lower detection threshold will increase the resolution of fault-zone structural features and define spatio-temporal characteristics in the seismicity at $M \sim> -1.0$, where occurrence rates are dramatically higher than those captured by the surface sites of the NCSN. This new data collection will contribute to improved working models for the Hayward fault. The bedrock ground motion recordings are being used to provide input for estimating the likely responses of the bridges to large, potentially damaging earthquakes. Combined with the improved Hayward fault models, source-specific response calculations can be made.

The Hayward Fault Network (HFN) consists of two parts. The Northern Hayward Fault Network (NHFN) is operated by the BSL and currently consists of 20 stations, including those located on the Bay bridges. This network is considered part of the BDSN and uses the network code BK. The Southern Hayward Fault Network (SHFN) is operated by the USGS and currently consists of 5 stations. This network is considered part of the NCSN and uses the network code NC. This chapter is primarily focused on the NHFN and activities associated with the BSL operations.

## 2.  NHFN Overview

All sites of the HFN have six-component borehole sensor packages which were designed and fabricated at LBNL's Geophysical Measurement Facility by Don Lippert and Ray Solbau, with the exception of site SFAB. Three channels of acceleration are provided by Wilcoxon 731A piezoelectric accelerometers and three channels of velocity are provided by Oyo HS-1 4.5 Hz geophones (Table 5.2). Sensors are installed at depths of 100-300 m and provide signals to the on-site data loggers (Quanterra Q4120 and Q730, Nanometrics HRD24, or RefTek 72A-07 systems).

The 0.1-400 Hz Wilcoxon accelerometers have lower self-noise than the geophones above about 25-30 Hz, and remain on scale and linear to 0.5 g. In tests performed in the Byerly vault at UC Berkeley, the Wilcoxon is considerably quieter than the FBA-23 at all periods, and is almost as quiet as the STS-2 between 1 and 50 Hz.

Eight of the NHFN sites have Quanterra data loggers with continuous telemetry to the BSL. Similar to BDSN sites, these stations are capable of on-site recording and local storage of all data for more than one day and have batteries to provide backup power. Signals from these stations are digitized at a variety of data rates up to 500 Hz at 24-bit resolution (Table 5.3). In contrast to the BDSN implementation, the NHFN data loggers employ casual FIR filters at high data rates and acausal FIR filters at lower data rates. Because of limitations in telemetry bandwidth and disk storage, these 7 sites transmit triggered data at 500 sps, using the Murdock, Hutt, and Halbert (MHH) event detection algorithm (*Murdock and Hutt*, 1983), and continuous data at reduced rates (100, 20 and 1 sps) to the BSL.

The remaining 12 sites of the NHFN have in the past recorded data using RefTek data loggers. These sites do not have continuous telemetry for acquisition and require visits from BSL staff for data recovery. Seven of these sites located on the Bay Bridge are scheduled to be upgraded with Quanterra data loggers and continuous telemetry in the fall of 2002 (see Figure 11.2 in Chapter 11). The Bay Bridge component of the NHFN has been
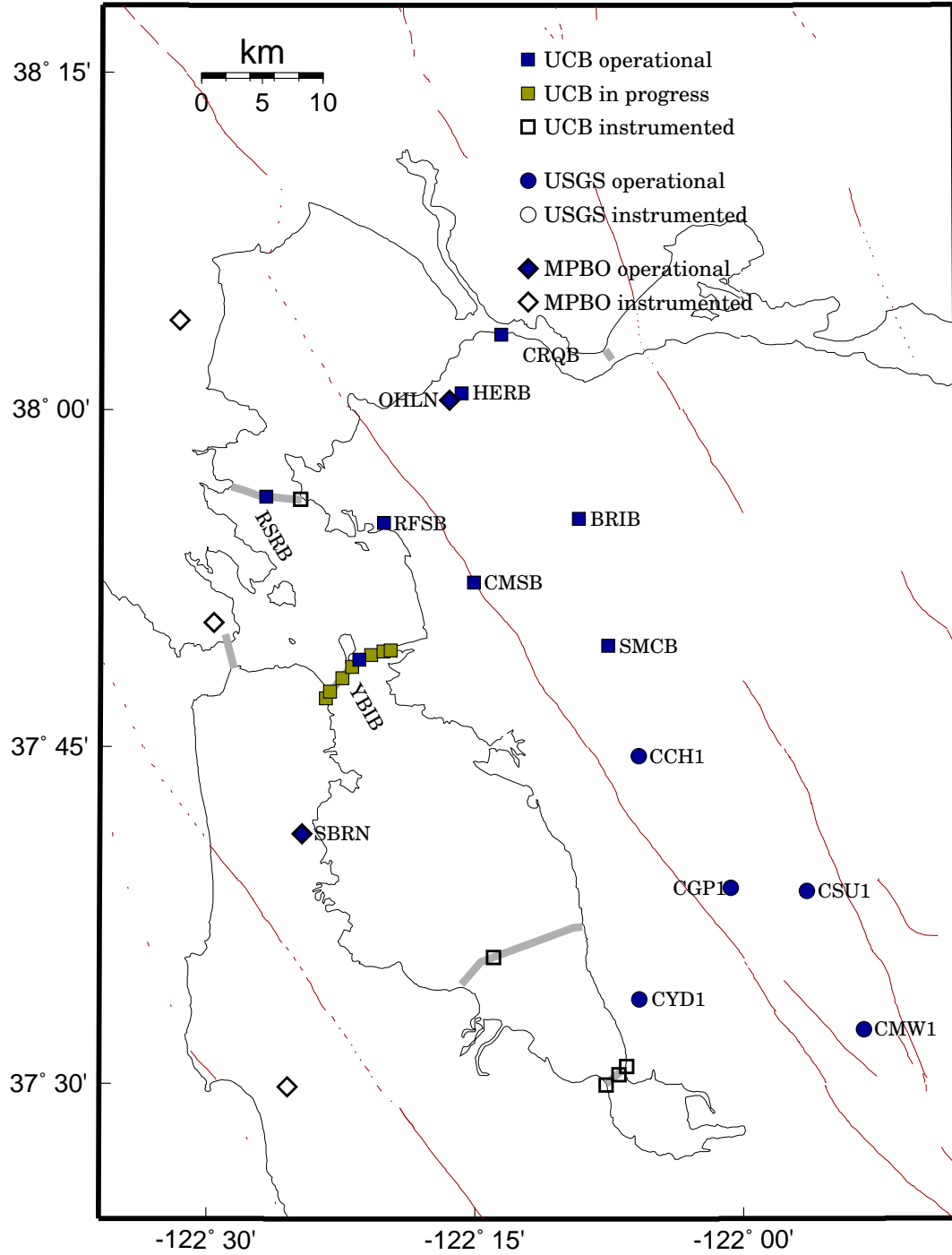
Figure 5.1: Map showing the locations of the HFN stations operated by the BSL (NHFN - squares) and the USGS (SHFN - circles) and Mini-PBO stations (diamonds) in the San Francisco Bay Area. Operational sites are filled, while sites in progress are grey. Other instrumented boreholes are indicated as open symbols.

delayed during the past year, primarily due to the major effort required to upgrade the HRSN (Chapter 6).

Signals from the 5 SHFN stations are digitized by Nanometrics data loggers at 200 sps and transmit continuous data to Menlo Park by radio. The digital data streams are processed by the Earthworm system with the NCSN data and waveforms are saved when the Earthworm detects an event.

As part of the USGS and BSL collaboration on the HFN, data from the NHFN and SHFN sites with continuous telemetry are shared in near real-time. NHFN data are transmitted to the USGS and SHFN data are transmitted to the BSL.

Experience has shown that the MHH detector does not provide uniform triggering across the NHFN on the smallest events of interest. In order to insure the recovery of 500 sps data for these earthquakes, a central-site controller has recently been implemented at the BSL using the 500 sps vertical component geophone data for event detection. Originally the 100 sps vertical component geophone data was used for event detection but the bandwidth proved to be inadequate for detection of the smaller events where most of the seismic wave energy was at frequencies above 40 Hz. Triggers from this controller will be used to recover the 500 sps data from the NHFN data loggers.

Data from the NHFN and SHFN are archived at the NCEDC. At this time, the tools are not in place to archive the Hayward fault data together. The NHFN data are archived with the BDSN data, while the SHFN are archived with the NCSN data (Chapter 13). However, the new central-site controller will provide the capability to both include SHFN data in the event detection and extract SHFN waveforms for these events in the future.

As originally planned, the Hayward Fault Network was to consist of 24 to 30 stations, 12-15 each north and south of San Leandro, managed respectively by UCB and USGS. This is not happening quickly, although west of the fault, Caltrans has provided sites along the Bay bridges. This important contribution to the Hayward Fault Network has doubled the number of sites with instrumentation. At times, Caltrans provides holes of opportunity away from the bridges (e.g., HERB), so we have plans for additional stations that will bring the network geometry to a more effective state for imaging and real-time monitoring of the fault.

As a check on the calibration and an example of the capabilities of a borehole installed network, we compare the bandpass filtered (0.3-2 Hz) ground displacements, as inferred from the vertical component accelerometer and from the vertical component geophone data streams recorded at BRIB, CMSB, CRQB, HERB, OHLN, SBRN (the newest MPBO station, sited on San Bruno Mtn, San Francisco Peninsula), and RFSB, for a M 7.7 deep focus earthquake that occurred in the Fiji Islands at a depth

| Sensor | Channel | Rate (sps) | Mode | FIR |
|---|---|---|---|---|
| Accelerometer | CL? | 500.0 | T | Ca |
| Accelerometer | HL? | 100.0 | C | Ca |
| Accelerometer | BL? | 20.0 | C | Ac |
| Accelerometer | LL? | 1.0 | C | Ac |
| Geophone | DP? | 500.0 | T | Ca |
| Geophone | EP? | 100.0 | C | Ca |
| Geophone | BP? | 20.0 | C | Ac |
| Geophone | LP? | 1.0 | C | Ac |

Table 5.3: Typical data streams acquired at each NHFN site, with channel name, sampling rate, sampling mode and FIR filter type. C indicates continuous; T triggered; Ca causal; and Ac acausal. The 100 sps channels (EP & HL) are only archived when the 500 sps channels are not available.

of 580 km. in Figure 5.2.

## 3.   2001-2002 Activities

During this year, two stations of the NHFN continued to be not operational. YBIB was shut down when power was cut off in August 2000 and RSRB was taken offline in April 2001 during the retrofit project on the Richmond-San Rafael Bridge. YBIB is anticipated to return after solar panels are installed in late 2002/early 2003. No estimate of the return of RSRB is currently available.

### 3.1   Station Maintenance

The most pervasive problem at NHFN stations equipped with Q4120 data loggers is power line noise (60 Hz and its harmonics at 120, 180, and 240 Hz). This noise reduces the sensitivity of the MHH detectors.

Whenever a NHFN station is visited, the engineer at the site and a seismologist at the BSL work together to expedite the testing process, especially when attempting to identify and correct ground-loop faults which generally induce significant 60, 120, 180, and 240 Hz seismic signal contamination due to stray power line signal pickup, generally inductively coupled and aggravated by the presence of ground loops.

**CMSB**

Replaced batteries. Repaired signal cable where it was chewed by rodents. Q4120 is drawing 2.9 amps. The preamp draws about 200 ma which is correct. This indicates higher than normal current (Q4120 current should be ∼2.3 amps) into the Q4120 and gradual failure of one of the circuits.

| Code | Net | Latitude | Longitude | Elev (m) | Over (m) | Date | Location |
|------|-----|----------|-----------|----------|----------|------|----------|
| BRIB | BK | 37.91886 | -122.15179 | 219.7 | 108.8 | 1995/07 - current | BR, Orinda |
| CMSB | BK | 37.87195 | -122.25168 | 94.7 | 167.6 | 1994/12 - current | CMS, Berkeley |
| CRQB | BK | 38.05578 | -122.22487 | -25.0 | 38.4 | 1996/07 - current | CB |
| HERB | BK | 38.01250 | -122.26222 | -25.0 | 217.9 | 2000/05 - current | Hercules |
| RFSB | BK | 37.91608 | -122.33610 | -27.3 | 91.4 | 1996/01 - current | RFS, Richmond |
| RSRB | BK | 37.93575 | -122.44648 | -48.0 | 109 | 1997/06 - current * | RSRB, Pier 34 |
| SMCB | BK | 37.83881 | -122.11159 | 180.9 | 3.4 | 1997/12 - current | SMC, Moraga |
| YBIB | BK | 37.81420 | -122.35923 | -27.0 | 61 | 1997/12 - current * | BB, Pier E2 |
| OHLN | BK | 38.00742 | -122.27371 |  |  | 2001/07 - current | MPBO, Ohlone Park |
| SBRN | BK | 37.68562 | -122.41127 |  |  | 2001/08 - current | MPBO, San Bruno Mtn. |
| SFAB | BK | 37.78610 | -122.3893 |  | 0.0 | 1998/06 - current | BB, SF Anchorage |
| W02B | BK | 37.79120 | -122.38525 |  | 57.6 | 1996/04 - current | BB, Pier W2 |
| W05B | BK | 37.80100 | -122.37370 |  | 36.3 | 1997/10 - current | BB, Pier W5 |
| YBAB | BK | 37.80940 | -122.36450 |  | 3.0 | 1998/06 - current | BB, YB Anchorage |
| E07B | BK | 37.81847 | -122.34688 |  | 134.0 | 1996/02 - current | BB, Pier E7 |
| E17B | BK | 37.82086 | -122.33534 |  | 160.0 | 1995/08 - current | BB, Pier E17 |
| BBEB | BK | 37.82167 | -122.32867 |  | 150 | 1994/03 - 1995/10 | BB, Pier E23 |
| DB1B | BK | 37.49947 | -122.12755 |  | 0.0 | 1994/07 - 1994/09 | DB, Pier 1 |
|  |  |  |  |  | 1.5 | 1994/09 - 1994/09 |  |
|  |  |  |  |  | 71.6 | 1994/09 - 1994/09 |  |
|  |  |  |  |  | 228.0 | 1993/08 - current |  |
| DB2B | BK | 37.50687 | -122.11566 |  |  | 1994/07 - current | DB, Pier 27 |
|  |  |  |  |  | 189.2 | 1992/07 - 1992/11 |  |
| DB3B | BK | 37.51295 | -122.10857 |  | 1.5 | 1994/09 - 1994/11 | DB, Pier 44 |
|  |  |  |  |  | 62.5 | 1994/09 - 1994/09 |  |
|  |  |  |  |  | 157.9 | 1994/07 - current |  |
| SM1B | BK | 37.59403 | -122.23242 |  | 298.0 | not recorded | SMB, Pier 343 |
| RB2B | BK | 37.93372 | -122.41313 |  | 44 | 1997/06 - current | RSRB, Pier 58 |
| CCH1 | NC | 37.7432 | -122.0967 | 226 |  | 1995/05 - current | Chabot |
| CGP1 | NC | 37.6454 | -122.0114 | 340 |  | 1995/03 - current | Garin Park |
| CMW1 | NC | 37.5403 | -121.8876 | 343 |  | 1995/06 - current | Mill Creek |
| CSU1 | NC | 37.6430 | -121.9402 | 499 |  | 1995/10 - current | Sunol |
| CYD1 | NC | 37.5629 | -122.0967 | -23 |  | 2002/09 - current | Coyote |

Table 5.1: Stations of the Hayward Fault Network. Each HFN station is listed with its station code, network id, location, operational dates, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame. The elevation of the well head (in meters) is relative to the WGS84 reference ellipsoid. The overburden is given in meters. The date indicates either the upgrade or installation time. The abbreviations are: BB - Bay Bridge; BR - Briones Reserve; CMS - Cal Memorial Stadium; CB - Carquinez Bridge; DB - Dumbarton Bridge; MPBO - mini-Plate Boundary Observatory RFS - Richmond Field Station; RSRB - Richmond-San Rafael Bridge; SF - San Francisco; SMB - San Mateo Bridge; SMC - St. Mary's College; and, YB - Yerba Buena. The * for YBIB and RSRB indicates that the stations are not currently operational at this time. RSRB is shut down while Caltrans is retrofitting the Richmond-San Rafael bridge (as of April 19, 2001) and YBIB has been off-line since August 24, 2000 when power cables to the site where shut down. The table also includes 2 MPBO stations which became operational in the last year.

| Site | Geophone | Accelerometer | Z | H1 | H2 | Data logger | Notes | Telemetry |
|---|---|---|---|---|---|---|---|---|
| BRIB | Oyo HS-1 | Wilcoxon 731A | -90 | 79 | 349 | Q4120 | Acc. failed, Dilat. | FR |
| CMSB | Oyo HS-1 | Wilcoxon 731A | -90 | 19 | 109 | Q4120 | | FR |
| CRQB | Oyo HS-1 | Wilcoxon 731A | -90 | 251 | 341 | Q4120 | | FR |
| HERB | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Q4120 | | FR |
| RFSB | Oyo HS-1 | Wilcoxon 731A | -90 | 256 | 346 | Q4120 | | FR |
| RSRB | Oyo HS-1 | Wilcoxon 731A | -90 | 50 | 140 | Q4120 | 2 acc. failed | FR |
| SMCB | Oyo HS-1 | Wilcoxon 731A | -90 | 76 | 166 | Q4120 | Posthole | FR |
| YBIB | Oyo HS-1 | Wilcoxon 731A | -90 | 257 | 347 | Q4120 | Z geop. failed | Radio |
| OHLN | Mark L-22 | | -90 | TBD | TBD | Q4120 | Tensor. | FR |
| SBRN | Mark L-22 | | -90 | TBD | TBD | Q4120 | Tensor. | FR |
| SFAB | None | LLNL S-6000 | TBD | TBD | TBD | RefTek 72A-07 | Posthole | |
| W02B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| W05B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| YBAB | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| E07B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| E17B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| BBEB | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | None at present | Acc. failed | |
| DB1B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | Acc. failed | |
| DB2B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| DB3B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | Acc. failed | |
| SM1B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | None at present | | |
| RB2B | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | RefTek 72A-07 | | |
| CCH1 | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Nanometrics HRD24 | Dilat. | Radio |
| CGP1 | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Nanometrics HRD24 | Dilat. | Radio |
| CMW1 | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Nanometrics HRD24 | Dilat. | Radio |
| CSU1 | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Nanometrics HRD24 | Dilat. | Radio |
| CYD1 | Oyo HS-1 | Wilcoxon 731A | -90 | TBD | TBD | Nanometrics HRD24 | Dilat. | Radio |

Table 5.2: Instrumentation of the HFN as of 06/30/2002. Every HFN downhole package consists of co-located geophones and accelerometers, with the exception of OHLN and SFAB. 6 HFN sites also have dilatometers (Dilat.) and the 2 MPBO sites have tensor strainmeters (Tensor.) 7 NHFN sites have Quanterra data loggers with continuous telemetry to the BSL. The remaining sites use RefTek data loggers for on-site recording. The 5 SHFN sites have Nanometrics data loggers with radio telemetry to the USGS. The orientation of the sensors (vertical - Z, horizontals - H1 and H2) are indicated where known or identified as "to be determined" (TBD).
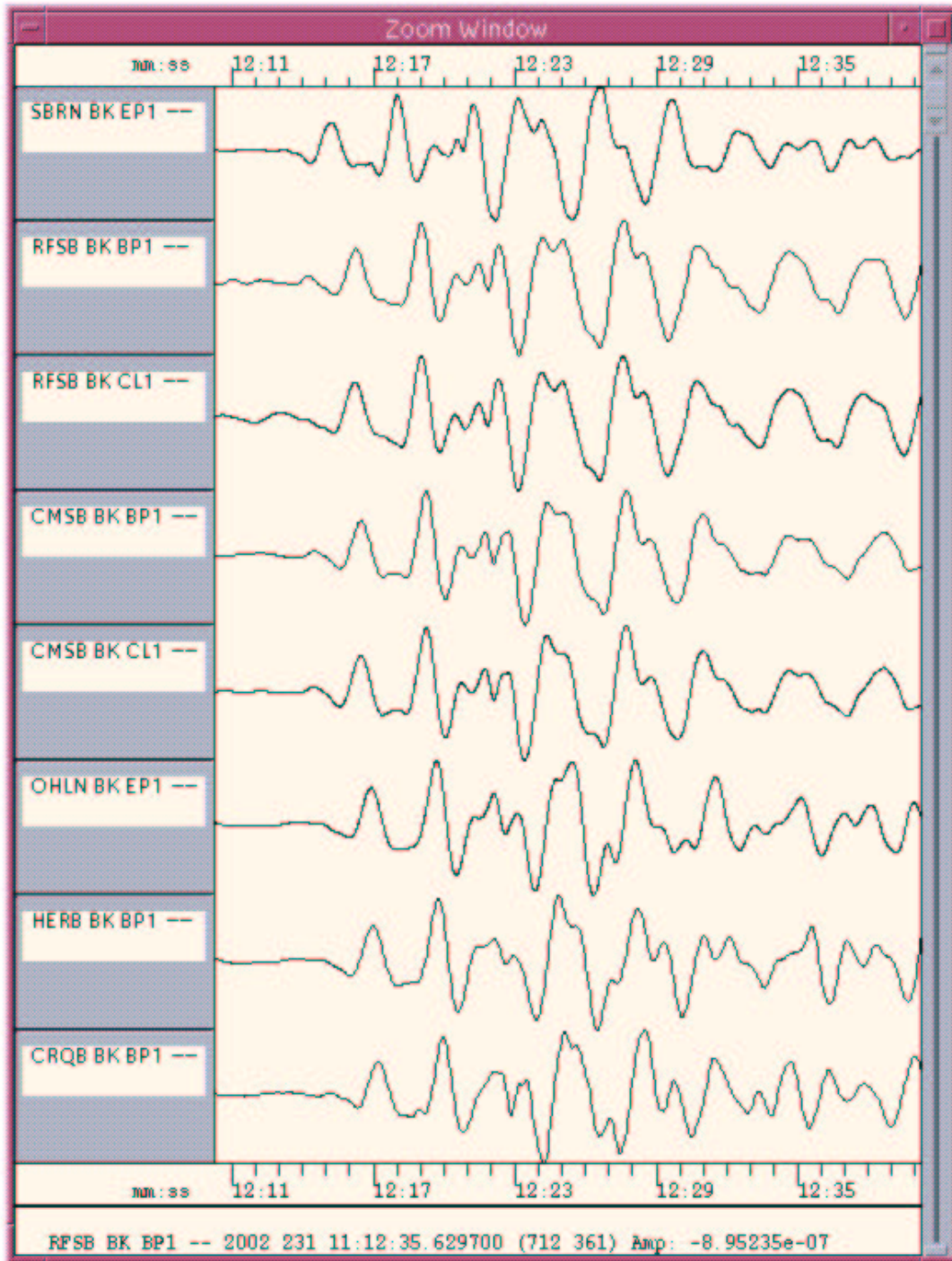
Figure 5.2: Ground displacement waveforms, inferred from accelerometer and velocity sensors at six borehole stations (4 NHFN and 2 MPBO) for the 19 August 2002 deep focus Fiji Islands teleseism (11:01 UT, -21.70, -179.51, 580 km deep, M 7.7). The waveforms have been 0.3-2 Hz bandpass filtered and deconvolved to ground displacement and ordered by epicentral distance for comparison. The highly similar waveforms indicate that the instruments are operating normally and that the transfer functions are correct.

### HERB

Q4120 installed on 18 September, 2001. Geophone channel experiencing large 60 Hz and harmonics signals apparently due to the presence of ground loops. Investigation of this signal contamination continues.

### RFSB

The Q4120 serial ports failed due to faulty capacitors.

### SMCB

Experienced numerous intermittent telemetry problems during year. Rebuilt power system and installed new FRAD, power supply and batteries in a second Hoffman box. Q4120 failed due to a blown hard wired fuse on circuit board. Replaced fuse and reinstalled Q4120.

## 3.2   Event Detection

As noted in the Introduction, one of the purposes of the HFN is to lower the threshold of microearthquake detection. Towards this goal, we have been developing four new algorithms: a pattern recognition approach to identify small events; a phase onset time detector with sub-sample timing resolution, and; a phase coherency method for single component identification of highly similar events, and; a spectrogram method for characterizing the frequency-time power distribution of the observed seismic waveforms.

### Pattern Recognition

In order to improve the detection and analysis of small events (down to $M_L \sim$-1.0) some specialized algorithms are being developed. The Murdock-Hutt detection algorithms used by MultiSHEAR, which basically flags an event whenever the short-term average exceeds a longer-term average by some threshold ratio, is neither appropriate for nor capable of detecting the smallest seismic events. One solution is to use a pattern recognition approach to identify small events associated with the occurrence of an event which was flagged by the REDI system. Tests have indicated that the pattern recognition detection threshold is $M_L \sim$ -1.0 for events occurring within $\sim$10 km of a NHFN station. The basic idea is to use a quarter second of the initial P-wave waveform, say, as a master pattern to search for similar patterns that occur within $\pm$ one day, say, of the master event. Experimentally, up to six small CMSB recorded events, at the $M_L \sim$ -1.0 threshold and occurring within $\pm$ one day of a master pattern, have been identified.

The pattern recognition method is CPU intensive, however, and it will require a dedicated computer to handle the pattern recognition tasks. To expedite the auto-correlation processing of the master pattern, an integer arithmetic cross-correlation algorithm has been de-veloped which speeds up the requisite processing by an order of magnitude.

### Phase Onset Time Detection

The phase onset time detector makes use of the concept that the complex spectral phase data, over the bandwidth of interest (ie, where the SNR is sufficiently high), will sum to a minimum at the onset of an impulsive P-wave. The algorithm searches for the minimum phase time via phase shifting in the complex frequency domain over the bandwidth where the SNR is above 30 dB, say, to identify the onset time of the seismic phase. The algorithm requires that the recorded waveforms be deconvolved to absolute ground displacement. This implicitly requires that any acausality in the anti-aliasing filtration chain, such as the FIR filters used in the BDSN Quanterra data loggers, be removed. The algorithm typically resolves P-wave onset times to one-fiftieth of the sample interval or better.

### Phase Coherency

The spectral phase coherency algorithm was developed to facilitate high resolution quantification of the similarities and differences between highly similar Hayward fault events which occur occur months to years apart. Figure 5.3 shows an example of three highly similar $M_L \sim$1.3 events. The 0.997 complex spectral phase coherency between the waveforms for events a (1998.202.132956) and c (2000.170.171607) implies that the centroids of these two events are not more than $\sim$20 cm apart spatially. Extrapolation of magnitude versus fault rupture area, empirically derived using M $\sim$4-7 earthquakes, yields an expected rupture radius of $\sim$20 m for a M 1.3 event. However, the 0.997 phase coherency implies that the source rupture time histories can not differ by more than $\sim$ 6 $\mu$sec which, in turn, implies that either the rupture spatial-temporal histories of the two sources are virtually identical over a radius of $\sim$20 m or that the sources have a high stress drop and a rupture radius of order a few meters at most. Of these two possibilities, the latter is considered the most likely.

The resolution of the complex spectral phase coherency methodology is an order of magnitude better that the cross correlation method which is commonly used to identify highly similar events with resolution of order a few meters.

### Spectrogram Analysis

Figure 5.4 shows an example of a spectrogram derived from the CMSB Z-component ground acceleration recording of a M 1.3 local earthquake (1998.202.132956). Most of the power is in the first few seconds and coincides with the P-wave and S-wave arrivals and their immediate coda. There is little energy above $\sim$110 Hz and after

~5 seconds for this M 1.3 event and ~10 km propagation path. Spectrograms can be used as a tool to help in the characterization of seismic sources and propagation paths.
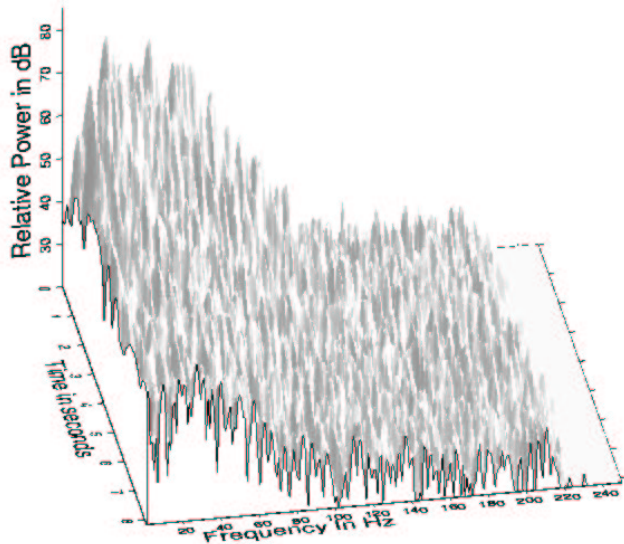


Figure 5.4: Spectrogram of the CMSB Z-component ground accelerations for the M 1.3 earthquake (Inset (a) in Figure 5.3). Plotted is relative power (dB) as a function of time and frequency.

### 3.3 New Installations

**San Francisco-Oakland Bay Bridge Stations**

The infrastructure at seven stations along the San Francisco-Oakland Bay Bridge (SFAB, W02B, W05B, YBAB, E07B, E17B, and BBEB) was upgraded with the installation of weatherproof boxes, power, and telemetry in anticipation of installing Q730 data loggers and telemetering the data back to Berkeley in the fall of 2002.

**Mini-PBO**

The stations of the Mini-PBO project (Chapter 9) are equipped with borehole seismometers. As these stations have become operational, they augment HFN coverage (Figure 5.1). In the last year, OHLN at Ohlone Park, Hercules, has added to the coverage in the vicinity of San Pablo Bay and provides an interesting comparison with the NHFN station HERB.

## 4. Acknowledgements

Thomas V. McEvilly passed away in February 2002 (Chapter 2). Tom was instrumental in developing the Hayward Fault Network, and without his dedication and hard work the creation and continued operation of the NHFN would not have been possible.

Under Bob Nadeau's and Doug Dreger's general supervision, Rich Clymer, Wade Johnson, Doug Neuhauser, Bob Uhrhammer, Bill Karavas, John Friday, and Dave Rapkin all contribute to the operation of the NHFN. Bob Uhrhammer and Lind Gee contributed to the preparation of this chapter.

Partial support for the NHFN is provided by the USGS through the NEHRP external grant program. Expansion of the NHFN has been made possible through generous funding from Caltrans, with the assistance of Pat Hipley. Larry Hutchings of LLNL has been an important collaborator on the project.

## 5. References

Murdock, J., and C. Hutt, A new event detector designed for the Seismic Research Observatories, *USGS Open-File-Report 83-0785,* 39 pp., 1983.
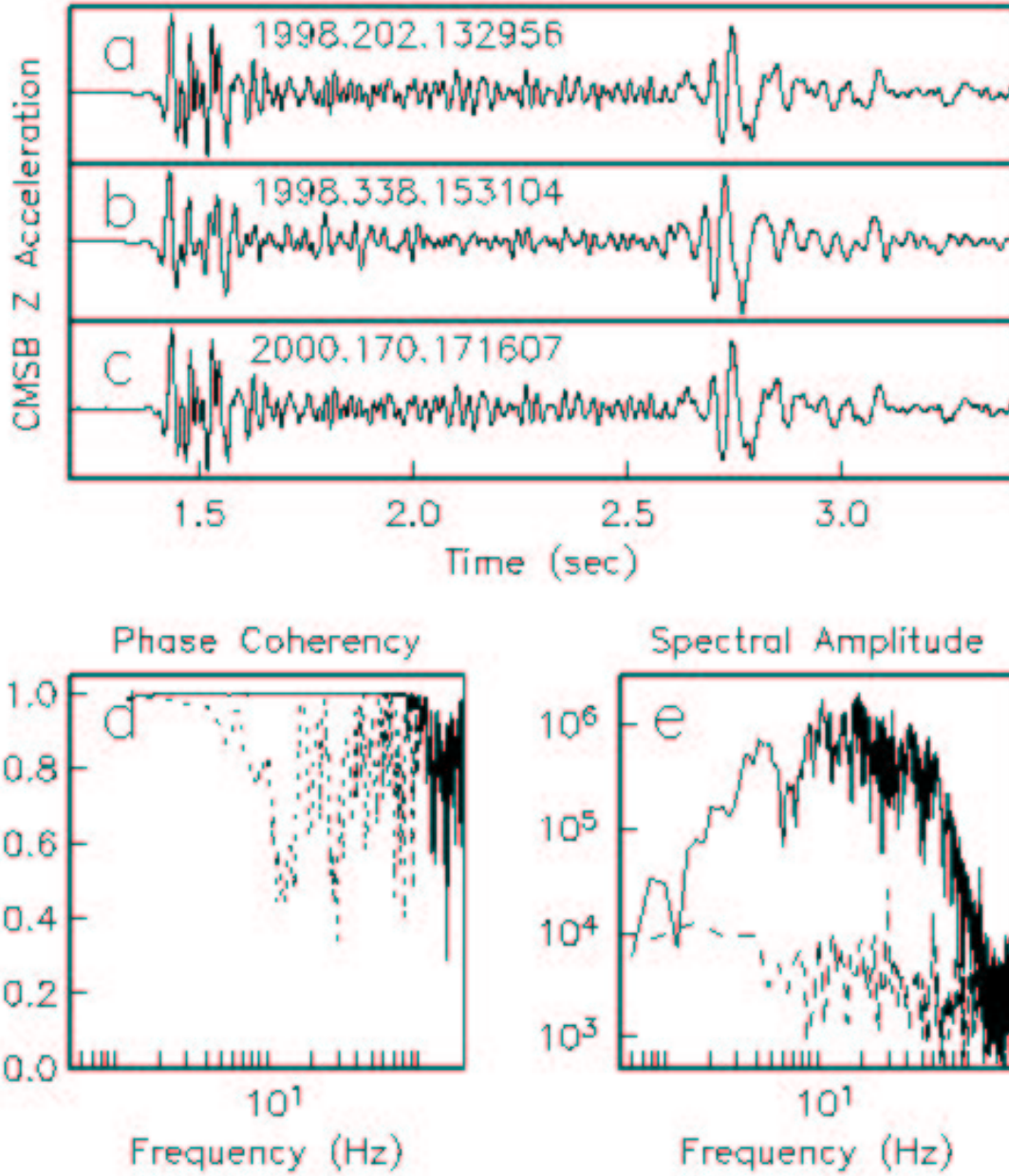
Figure 5.3: Example of using complex spectral phase coherency as a discriminant for analyzing a trio of highly similar earthquakes which occurred on the Hayward fault approximately 6 km northwest of Berkeley. The borehole station CMSB (197 m depth) raw Z-component acceleration data for the three earthquakes are shown in parts (a), (b) and (c). Note that the M 1.3 waveforms in (a) and (c) are visually virtually identical while the M 1.7 waveforms in (b) differs in detail and it has a 11 msec shorter S-P interval than either (a) or (c). The Phase coherency between (a) and (c), shown as the solid line in (d) (calculated using 10 seconds of the Z-component waveforms starting $\sim 1.38$ seconds prior to the P-wave onset, i. e. using the entire waveform including through the S-wave coda), is 0.997 in the 2-80 Hz frequency band. The inference is that the (a) and (c) centroid locations differ by not more than 20 cm (assuming that the near source scatterers are isotropically distributed). The dashed line in (d) is the phase coherency between the (b) and (c) waveforms and the dips in the coherency at $\sim$15 Hz and $\sim$30 Hz can be interpreted as destructive interference caused by differences in their centroid locations of order 100 m (compatible with the $\sim$60 m along ray path differences in their S-P times). The solid and dashed lines in (e) are the (c) waveform signal and noise amplitude spectra, respectively. The SNR is 40+ dB in the $\sim$10-70 Hz band and above unity in the $\sim$1.5-110 Hz band and the change in slope above $\sim$65 Hz is interpreted as the corner frequency of the M 1.3 earthquake source.

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# Chapter 6

# Parkfield Borehole Network

## 1.  Introduction

The operation of the High Resolution Seismic Network (HRSN) at Parkfield, California began in 1987, as part of the U.S. Geological Survey initiative known as the Parkfield Prediction Experiment (PPE) (*Bakun and Lindh*, 1985).

Figure 6.1 shows the location of the network, its relationship to the San Andreas fault, sites of significance to previous and ongoing research using the HRSN, relocated earthquake locations, and the epicenter of the 1966 M6 earthquake that motivated the PPE. The HRSN records exceptionally high-quality data, owing to its 13 closely spaced three-component borehole sensors, its very wide bandwidth high frequency recordings (0-125 Hz), and its sensitivity (recording events below magnitude -1.0) due to the extremely low attenuation and background noise levels at the 200-300 m sensor depths (*Karageorgi et al.*, 1992).

Several aspects of the Parkfield region make it ideal for the study of small earthquakes and their relationship to tectonic processes.  These include the fact that the network spans the expected nucleation region of a repeating magnitude 6 event and the transition from locked to creeping behavior on the San Andreas fault, the availability of three-dimensional P and S velocity models, a very complete seismicity catalogue, a well-defined and simple fault segment, a homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip), and the planned drilling zone and penetration and instrumentation site of the San Andreas Fault deep observatory at depth (SAFOD) installation (see: `http://www.icdp-online.de/html/sites/sanandreas/objectives/proposal.html`).

In a series of journal articles and Ph.D. theses, we have presented the cumulative, often unexpected, results of this effort. They trace the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate-boundary loading, and they are forcing new thinking on the dynamic processes and conditions within the fault zone at the sites of recurring small earthquakes. Recent results are described in Chapter 15.

## 2.  HRSN Overview

### 2.1  1986 - 1998

The HRSN was installed in deep (200-300m) boreholes beginning in 1986. Sensors are 3-component geophones in a mutually orthogonal gimbaled package.  This ensures that the sensor corresponding to channel DP1 is aligned vertically and that the others are aligned horizontally.  In November 1987, the Varian well vertical array was installed and the first VSP survey was conducted, revealing clear S-wave anisotropy in the fault zone. During 1988, the original network was completed to a ten station 3-component 500 sps set of stations telemetered into a central detection/recording system operating in triggered mode and incorporating a deep (572 m) sensor in the Varian well string into the network. The Varian system was slaved in 1988, for about two years, to the Vibroseis control signals, allowing simultaneous recording of vibrator signals on both systems. In 1991, low-gain event recorders (from PASSCAL) were installed to extend the dynamic range to $M_L$ about 4.5.  The data acquisition system operated quite reliably until late 1996, when periods of unacceptably high down time developed, with as many as 7 of the remote, solar-powered telemetered stations down due to marginal solar generation capacity and old batteries, and recording system outages of a week or more became common.  In July of 1998 it failed permanently. The original acquisition system that failed was a modified VSP recorder acquired from LBNL, based on a 1980- vintage LSI-11 cpu and a 5 MByte removable Bernoulli system disk with a 9-track tape drive, configured to record both triggered microearthquake and Vibroseis (discontinued in 1997) data.  The system was remote and completely autonomous - tapes were mailed to Berkeley. The old system had one-sample timing uncertainty, and record length limitation because the tape write system recovery after event detection was longer than the length of the record, leaving the system off-line after record termination and until write recovery had completed.
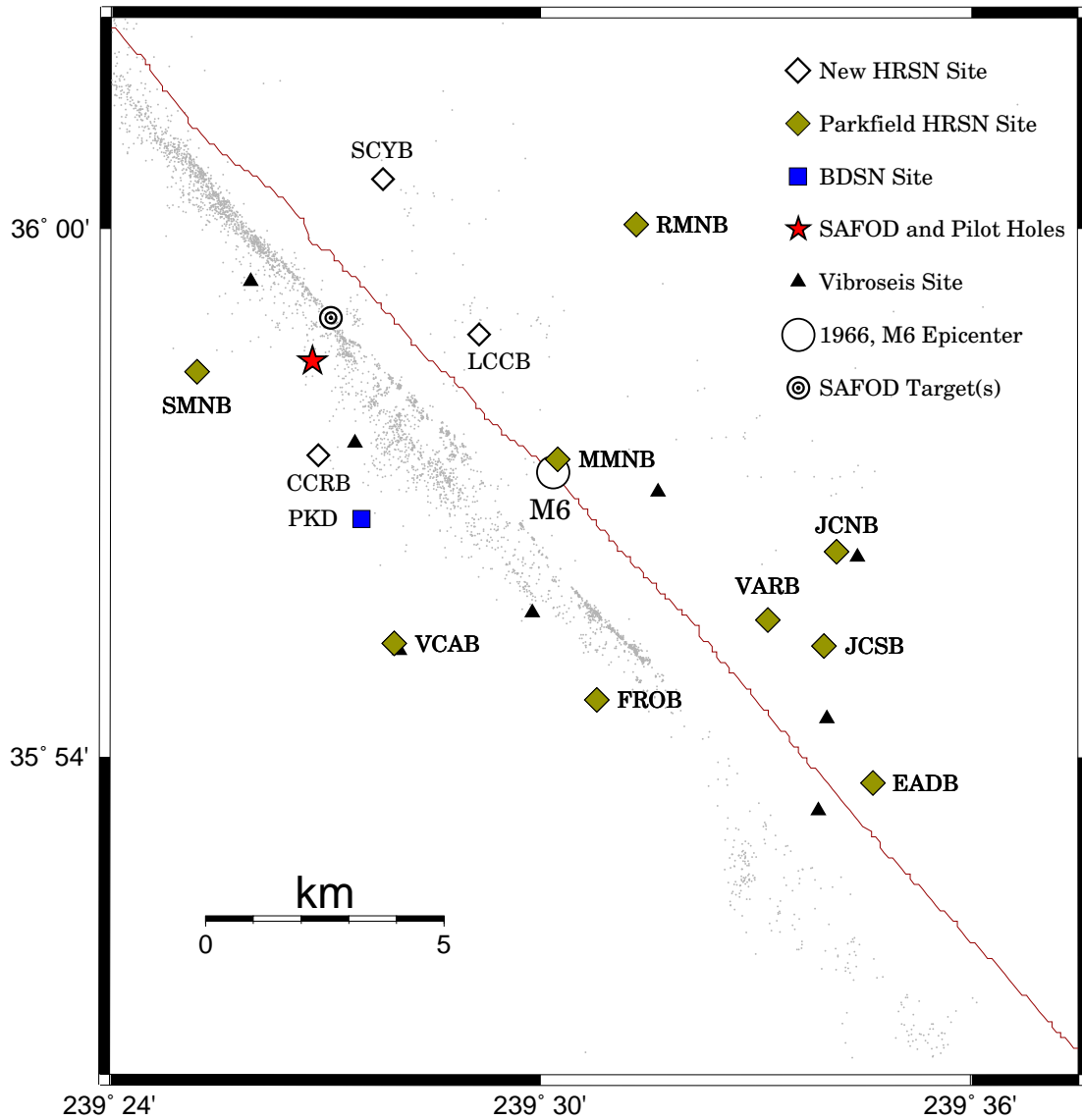
Figure 6.1: Map showing the San Andreas Fault trace, the location of the original 10 Parkfield HRSN stations (filled diamonds) and the 3 new sites (open diamonds), along with the BDSN station PKD (filled square). The locations of the 8 source points for the Vibroseis wave propagation monitoring experiment are represented by small black triangles. The epicenter of the 1966 M6 Parkfield main shock is located at the large open circle. The location of the pilot hole and proposed SAFOD drill site is shown by the filled star, and the location of the 2 alternative M2 repeating earthquake targets (70 meters apart) are shown as concentric circles. Seismicity relocated using an advanced 3-D double-differencing algorithm applied to a cubic splines interpolated 3-D velocity model (*Michelini and McEvilly*, 1991) is also shown (grey points). Station GHIB (Gold Hill, not shown) is located on the San Andreas Fault about 8 km to the Southeast of station EADB.

## 2.2    1998 - 1999

In fall 1998, the original HRSN acquisition system was replaced by 10 PASSCAL RefTek systems with continuous recording. This required the development of a major data handling procedure, in order to capture microearthquakes as small as M = -1.0, not seen on surface stations, since continuous telemetry to the BSL was not an option at that time.

In July, 1999 we had to reduce the network to four RefTeks at critical sites that would ensure continuity in the archive of characteristic events and temporal variations in recurrence. Properties of the 10 original sites are summarized in Table 6.2.

## 2.3    Upgrade and SAFOD Expansion

Thanks to emergency funding from the USGS NEHRP, we have replaced the original 10-station system with a modern 24-bit acquisition system (Quanterra 730 4-channel digitizers, advanced software using flash disk technology, spread-spectrum telemetry, Sun Ultra 10/440 central processor at the in-field collection point, with 56K frame-relay connectivity to Berkeley). The new system is now online and recording data continuously at a central site located on the California Department of Forestry (CDF) fire station in Parkfield.

We have also added three new borehole stations at the NW end of the network as part of the deep fault-zone drilling (San Andreas Fault Observatory at Depth - SAFOD) project, with NSF support, to improve resolution at the planned drilling target on the fault. Figure 6.1 illustrates the location of the proposed drill site (star) and the new borehole sites.

These three new stations use similar hardware to the main network, with the addition of an extra channel for electrical signals. Station descriptions and instrument properties are summarized in Tables 6.1 and 6.2. All HRSN Q730 data loggers employ FIR filters to extract data at 250 and 20 Hz (Table 6.3).

The remoteness of the drill site and new stations required the intermediate data collection point at Gastro Peak, with a microwave link to the CDF facility. We are sharing this link with the PASSCAL broadband array deployed around the drill site by the University of Wisconsin and the Rensselaer Polytechnic Institute. We are using the HRSN triggering algorithm in a joint triggering scheme which will allow the 60-station array to identify events on the lower noise, greater sensitivity of the borehole network. This has significantly increased event detection and reduced false triggers for the 60-station network data.

Figure 6.2 shows the telemetry system for the upgraded HRSN. The HRSN stations use SLIP to transmit TCP and UDP data packets over bidirectional spread-spectrum radio links between the on-site data acquisition systems and the central recording system at the CDF. Six of the sites transmit directly to a router at the central recording site. The other seven sites transmit to a router at Gastro Peak, where the data are aggregated and transmitted to the central site over a 4 MBit/second digital 5.4 GHz microwave link. The microwave link was installed to support the current IRIS PASSCAL broadband array deployment in Parkfield, and is shared by the HRSN and PASSCAL. All HRSN data are recorded to disk at the CDF site. A modified version of the REDI real-time system detects events from the HRSN data, creates event files with waveforms from the HRSN and PASSCAL networks, and sends the event data in near real-time to UC Berkeley.

The upgraded system is compatible with the data flow and archiving common to all the elements of the BDSN/NHFN and the NCEDC, and is providing remote access and control of the system. It is also providing data with better timing accuracy and longer records which are to eventually flow seamlessly into NCEDC. The new system solves the problems of timing resolution, dynamic range, and missed detections, in addition to providing the added advantage of conventional data flow (the old system recorded SEGY format).

# 3.    2001-2002 Activities

Significant efforts were made to identify and reduce noise and telemetry problems arising from the new recording, telemetry and site design this year. Detection, monitoring, and high-resolution recording of earthquakes down to the smallest possible magnitudes with the highest possible signal-to-noise (especially in the region of the proposed SAFOD drilling) is a major objective of the HRSN data collection. Consequently, elimination of all sources of unnaturally occurring noise is a primary goal. The minimization of data loss due to station outages and data-dropouts is also critical to this objective, since reduced station coverage degrades the sensitivity of network triggering.

## 3.1    Noise Reduction

The sophisticated HRSN data acquisition involves integration of a number of distinct components at each station (i.e., sensor, preamp, solar panels, solar regulator, batteries, Freewave radio, antenna, lightening arresters, and associated cabling, connectors and grounds).

This complex integration of station and communication components combined with a variety of associated concerns (e.g., ground loops, cable resistances, radio interference at stations and between stations, atmospheric effects on telemetry and power, the integration of older (pre-upgrade) hardware components with new upgraded components, failure of older components, and malfunctioning and unexpected performance characteristics of newer components) makes identification of specific causes

| Site | Net | Latitude | Longitude | Surf. (m) | Depth (m) | Date | Location |
|------|-----|----------|-----------|-----------|-----------|------|----------|
| EADB | BP | 35.89525 | -120.42286 | 499 | 245 | 01/1988 - | Eade Ranch |
| FROB | BP | 35.91078 | -120.48722 | 542 | 284 | 01/1988 - | Froelich Ranch |
| GHIB | BP | 35.83236 | -120.34774 | 433 | 63 | 01/1988 - | Gold Hill |
| JCNB | BP | 35.93911 | -120.43083 | 559 | 224 | 01/1988 - | Joaquin Canyon North |
| JCSB | BP | 35.92120 | -120.43408 | 487 | 155 | 01/1988 - | Joaquin Canyon South |
| MMNB | BP | 35.95654 | -120.49586 | 731 | 221 | 01/1988 - | Middle Mountain |
| RMNB | BP | 36.00086 | -120.47772 | 1198 | 73 | 01/1988 - | Gastro Peak |
| SMNB | BP | 35.97292 | -120.58009 | 732 | 282 | 01/1988 - | Stockdale Mountain |
| VARB | BP | 35.92614 | -120.44707 | 511 | 572 | 01/1988 - | Varian Well |
| VCAB | BP | 35.92177 | -120.53424 | 790 | 200 | 01/1988 - | Vineyard Canyon |
| CCRB | BP | 35.95716 | -120.55161 | 601 | 251 | 05/2001 - | Cholame Creek |
| LCCB | BP | 35.98006 | -120.51423 | 637 | 252 | 08/2001 - | Little Cholame Creek |
| SCYB | BP | 36.00942 | -120.53661 | 947 | 252 | 08/2001 - | Stone Canyon |

Table 6.1: Stations of the Parkfield HRSN. Each HRSN station is listed with its station code, network id, location, date of initial operation, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame, the surface elevation (in meters) is relative to mean sea level, and the depth to the sensor (in meters) below the surface. Coordinates and station names for the 3 new sites are given at the bottom.

| Site | Sensor | Z | H1 | H2 | RefTek 24 | RefTek 72-06 | Quanterra 730 |
|------|--------|---|----|----|-----------|--------------|---------------|
| EADB | Mark Products L22 | -90 | 170 | 260 | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| FROB | Mark Products L22 | -90 | 338 | 248 | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| GHIB | Mark Products L22 | 90 | failed | unk | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| JCNB | Mark Products L22 | -90 | 0 | 270 | 01/1988 - 12/1998 | 12/1998 - 06/2001 | 03/2001 - |
| JCSB | Geospace HS1 | 90 | 300 | 210 | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| MMNB | Mark Products L22 | -90 | 175 | 265 | 01/1988 - 12/1998 | 12/1998 - 06/2001 | 03/2001 - |
| RMNB | Mark Products L22 | -90 | 310 | 40 | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| SMNB | Mark Products L22 | -90 | 120 | 210 | 01/1988 - 12/1998 | 12/1998 - 06/2001 | 03/2001 - |
| VARB | Litton 1023 | 90 | 15 | 285 | 01/1988 - 12/1998 | 12/1998 - 07/1999 | 03/2001 - |
| VCAB | Mark Products L22 | -90 | 200 | 290 | 01/1988 - 12/1998 | 12/1998 - 06/2001 | 03/2001 - |
| CCRB | Mark Products L22 | -90 | N45W | N45E | - | - | 05/2001 - |
| LCCB | Mark Products L22 | -90 | N45W | N45E | - | - | 08/2001 - |
| SCYB | Mark Products L22 | -90 | N45W | N45E | - | - | 08/2001 - |

Table 6.2: Instrumentation of the Parkfield HRSN. Most HRSN sites have L22 sensors and were originally digitized with a RefTek 24 system. After the failure of the WESCOMP recording system, PASSCAL RefTek recorders were installed. In July of 1999, 6 of the PASSCAL systems were returned to IRIS and 4 were left at critical sites. The upgraded network uses a Quanterra 730 4-channel system. For the three new stations (bottom) horizontal orientations are approximate (N45W and N45E) and will be determined more accurately in the near future.

# Parkfield HRSN + PASSCAL Configuration



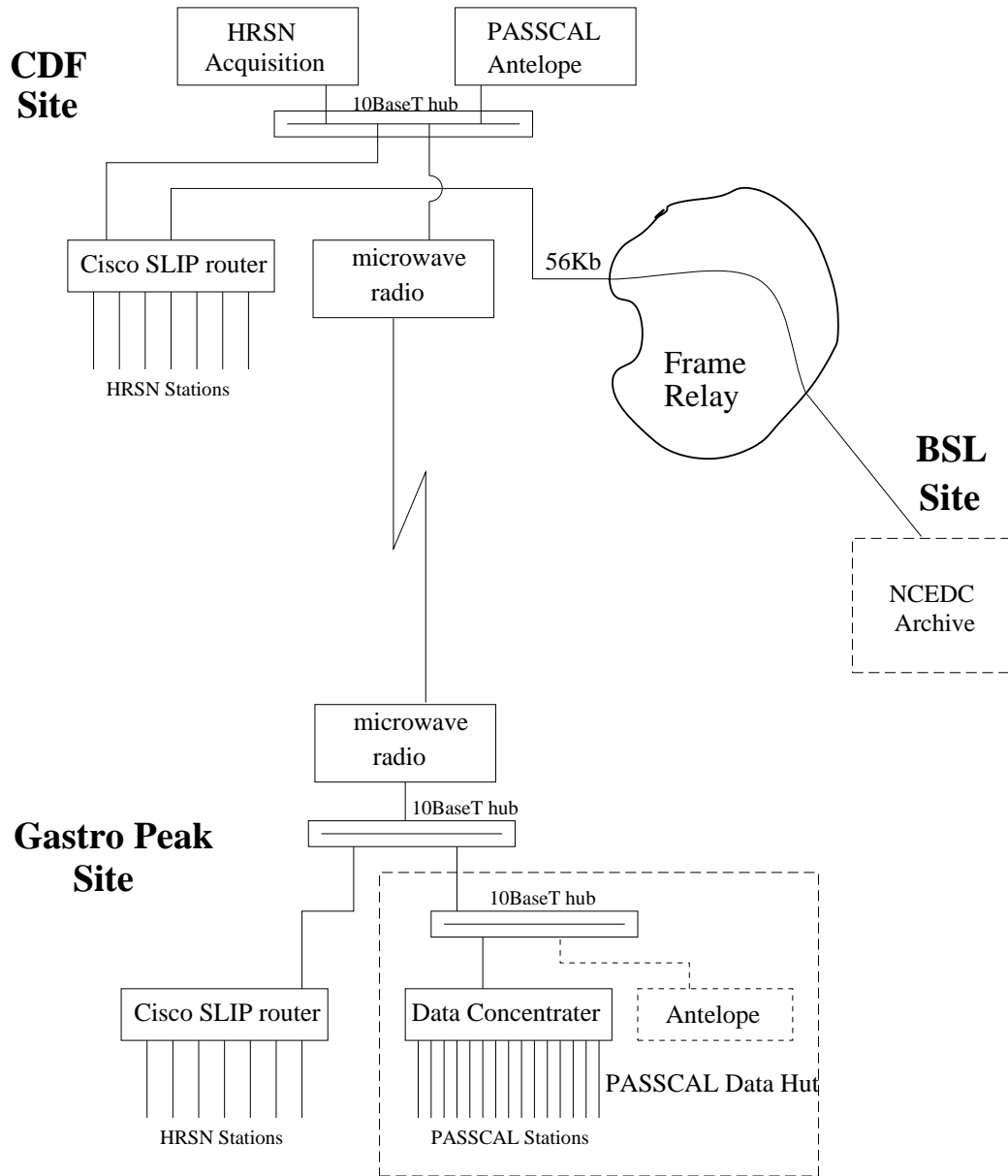Figure 6.2: HRSN data flow is illustrated in this figure. 6 stations are acquired directly at the CDF facility while the other 7 send data to a router at Gastro Peak. These data are aggregated and transmitted to the CDF site over a microwave radio link. The HRSN computer system runs a modified version of the REDI software and event files with waveforms are created and transmitted to the BSL over the frame-relay link.

of network generated (i.e. artificial) noise difficult to identify.

Over the past year, our exhaustive iterative testing of HRSN performance has identified three primary causes for the observed artificial noise. We have designed and have implemented or are in the process of implementing fixes.

### Power separation

Persistent 50 and 100 Hz noise sources affecting nearly all stations to varying degrees has been found to result from the interaction of the preamp and Quanterra systems through their common connection to a single power supply system. As a fix, we have separated preamp solar and battery power from the power provided to the rest of the data acquisition system at each station.

### Solar regulators

Regularly occurring spikes occurring during the daylight hours were observed in the continuous data streams and found to be due to the solar regulators. We have purchased and tested new solar regulators and are installing them at all the sites.

### Preamp Noise

A significant contribution source of artificial noise is the preamp amplification levels. In the upgraded system, preamps from the older network were used. During integration of the older preamps with the increased dynamic range capabilities of the 24-bit Quanterra system, gain settings of the preamps were reduced from x10000 to x80 in order to match signal sensitivity of the new system with the older one. While these lower preamp gain levels are still within the operational design of the preamps, they are no longer in their optimal range which enhances the contribution of preamp generated noise. Initially, this was not expected to be a significant problem. However, we have subsequently found that even the small increase in preamp noise that results from the preamp gain reduction can significantly impact the sensitivity of the network for detecting and recording the very smallest events.

Figure 6.3 shows the preamp noise effect from a test done at station EADB using background noise on day 134 of year 2002. Considerable signal hash is seen at gain levels of x80 (top 3-component waveforms), and significantly reduced when gains are increased to x1000 (lower waveforms). Since we are also interested in recording on-scale as large events as possible on the unique borehole, high-frequency broadband width HRSN, simply increasing gain levels on all stations is not an option. Doing so would cause the recording system to saturate at lower magnitudes. Our plan is to redesign the preamp opera-

tion characteristics so that their operation at gain levels of x80 is optimal.

A prototype preamp has been designed and built which is to be installed on an HRSN station for testing in the near future. If testing proves successful, installation of the redesigned preamps at all 13 stations is planned.
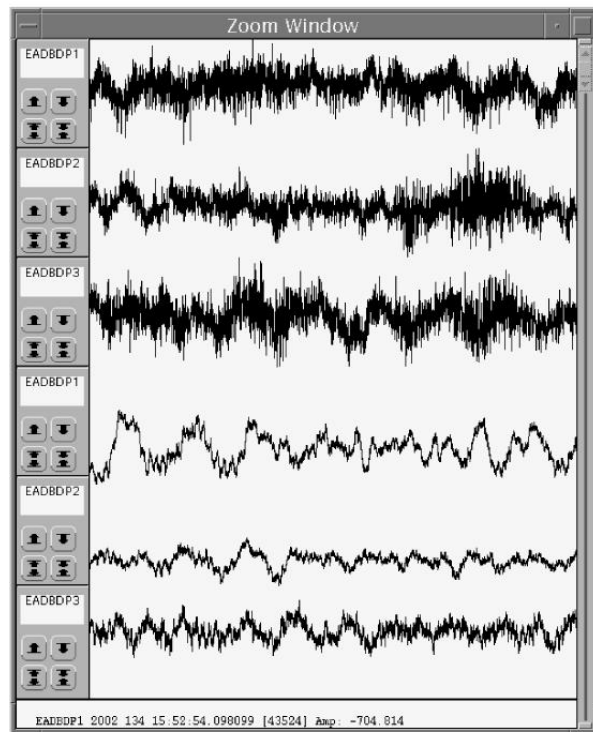


Figure 6.3: Preamp noise reduction test. Shown are 30 seconds of 3-component background signal recorded at station EADB on day 134 of 2002 at 1520 UTC (top 3) and 1550 UTC, when gain levels were set to x80 and x1000 respectively. Note the substantial reduction in preamp generated noise at high the higher gain. Network operation currently continues at x80 gain despite the preamp noise, in order to optimize the dynamic range capabilities. A prototype redesign of the preamp with optimized operational characteristics at x80 gain has been built and is to be field tested shortly.

## 3.2 Telemetry Dropouts

The cause of data dropouts at one of the new SAFOD critical stations (CCRB) was particularly difficult to determine. This problem did not appear during the early operation of CCRB, but became intermittent and then rather severe during the winter season. The majority of the time the transfer of data packets from CCRB to the the central data collection site were satisfactory. However, a strong positive correlation of the times of dropouts with the occurrence of earthquakes was observed (defi-

nitely not a desirable situation). It was eventually determined that the dropout problem was the result of an interplay involving data compression, station buffer size and marginal radio connectivity. For low amplitude background signals, the compression of data packets before telemetry was sufficient to prevent exceedence of the Quanterra buffer storage between periods of radio connectivity dropouts. However, during earthquakes, data compression is lower due to the higher amplitude signals of the quakes. This resulted in exceedence of the CCRB buffer storage capacity and data loss during earthquakes. Figure 6.4 shows an example of the dropout problem at an intermediate stage of its severity.

In an initial attempt to improve radio connectivity, installation of a large antenna dish was tried, but found to be an inadequate fix. A relay of the CCRB-Gastro Peak telemetry through a new repeater site was eventually required.
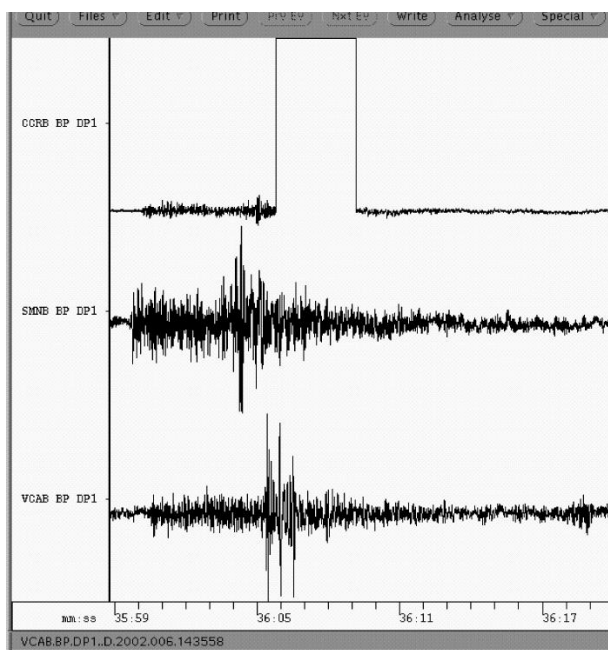


Figure 6.4: Data dropout example at station CCRB. Shown are 21 seconds of vertical component (DP1) waveform data from HRSN stations CCRB (top), SMNB (middle) and VCAB (bottom). Exceedence of local buffer capacity at CCRB caused data loss at about 5.5 seconds into the earthquake first arrival due to marginal radio telemetry and the reduced data compression possible for large amplitude (i.e. earthquake) signals.

## 3.3 SAFOD Pilot Hole Drilling

In June of 2002, drilling began on the SAFOD Pilot Hole (PH). The Pilot Hole was drilled to a depth of approximately 2 km (drilling was completed in late July).

Noise from the drilling was clearly visible at station CCRB, which may prove crucial for guiding SAFOD drilling in the future. Figure 6.5 shows the signal spectra below 65 Hz for 30 minutes of data recorded on the DP1 (vertical) channel at 250 sps generated by the SAFOD PH drilling on June 24 of 2002. The data are high-pass filtered at 0.5 Hz. The pilot hole was drilled within several 10's of meters from the planned SAFOD scientific hole and about 2 km due north of CCRB. Significant low frequency energy above background levels are seen below about 10 Hz.

Several significant spectral peaks can also be seen at about 1.5, 4.5, 6.5, and 10 Hz. The drill-bit spectra drops off sharply above 10 Hz. Comparable spectral amplitudes and character are observed on the DP1 and DP2 horizontal channels (not shown). The horizontal orientations (N45W and N45E) are bisected by the north-south oriented path from CCRB to the Pilot Hole. The frequency band and spectral character was also observed to change over longer time periods. We infer these changes to reflect either changes of the lithology being penetrated by the drill-bit or changes in the type of drill-bit or rotary speed. These changes further demonstrate the sensitivity of the borehole sensors for imaging bit generated noise.

With the completion of the pilot hole and the deployment of the downhole sensor strings, discussions are underway between the BSL and the USGS Menlo Park regarding use of the PH data within the HRSN system for enhanced triggering capability (see the "Future Directions" section).

## 3.4 Data Archive

At this time, continuous data streams on all 39 components are being recorded at 20 and 250 sps on the local HRSN computer at the CDF facility and archived on DLT tape. The 20 sps data are transmitted continuously to the BSL over the frame-relay linked and archived at the NCEDC. In addition, the 13 vertical component channels at 250 sps are also transmitted continuously to the BSL over the frame relay-circuit for purposes of fine tuning the triggering algorithm for detection at smallest possible magnitude levels.

An ongoing effort has been the development of a new earthquake triggering scheme, with the goal of replacing the continuous archive with triggered event gathers. A first cut version of the new scheme has been implemented and is already detecting earthquakes at an increased rate–about 3 times the number of earthquakes detected before the upgrade.

In order to facilitate the archive of the HRSN events, BSL staff are developing a Graphical User Interface

| Sensor | Channel | Rate (sps) | Mode | FIR |
|--------|---------|-----------|------|-----|
| Geophone | DP? | 250.0 | T | Ca |
| Geophone | BP? | 20.0 | C | Ac |

Table 6.3: Data streams currently being acquired at each HRSN site. Sensor type, channel name, sampling rate, sampling mode, and type of FIR filter are given. C indicates continuous; T triggered; Ac acausal; Ca causal. "?" indicates orthogonal vertical and 2 horizontal components.
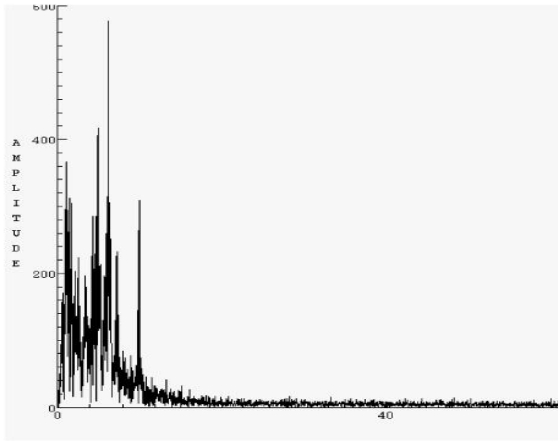


Figure 6.5: Signal spectra from SAFOD pilot hole drilling. Shown is the spectral amplitude below 65 Hz of 30 minutes of vertical component (DP1) data recorded by CCRB at 250 sps and high-pass filtered at 0.5 Hz. There is a marked absence of bit noise above 10 Hz, and distinct high amplitude spikes at about 1.5, 4.5, 6.5, and 10 Hz.

(GUI). The GUI will allow review of every trigger and either schedule the event to be archived or deleted (if it is noise, rather than an earthquake). The GUI will also allow the analysts to log problems, such as the noise spikes, and to characterize events based on S-P time.

## 4.  Examples of Data

The upgrade of the HRSN system from a 16- to 24-bit system has greatly improved its ability to record earthquakes over a wider magnitude range. Previously, clipping of waveforms would take place around magnitude 1.5. With the new system, earthquake with magnitudes between 4 and 5 are expected to be recorded on scale.

As an example of the HRSN waveform data quality at larger magnitudes, Figure 6.6 shows waveforms from the Sept. 6, 2002 magnitude 3.9 earthquake near Parkfield, CA. As expected the signal-to-noise (S/N) is excellent at all the borehole stations. Clipping of seismograms is absent, even at station EADB located only 3 km away from the epicenter. Figure 6.6 also includes seismograms from two PH sensors (PL11, at surface, and PL21, at 1.85 km depth).

Figure 6.6 illustrates the power of three-component recordings in borehole installations, as the the horizontal records give much better definition of the S-arrival than the vertical component alone. Vertical and horizontal components recored at the station closest to the M3.9 (EADB) and at the new station closest to the SAFOD drill site (CCRB) are shown. The apparent S-phase as seen on the vertical components arrives noticeably later ( 0.1 sec.) than the S-phase arrival seen on the horizontal components. S-arrival time differences of this magnitude can lead to location errors on the order a km or more The later arriving apparent S in the vertical records could be attributed to near surface forward scattered energy or possibly to Fault Zone Guided Wave arrivals, known to exist at Parkfield, rather than to the true S-phase.

Although the PH sensors are currently only recording vertical motion, the recordings of the deep sensors (1.85 km) should significantly aid in the detection of the very smallest events in the penetration zone. A significant delay in the P-arrival time of the M3.9 event at PL11
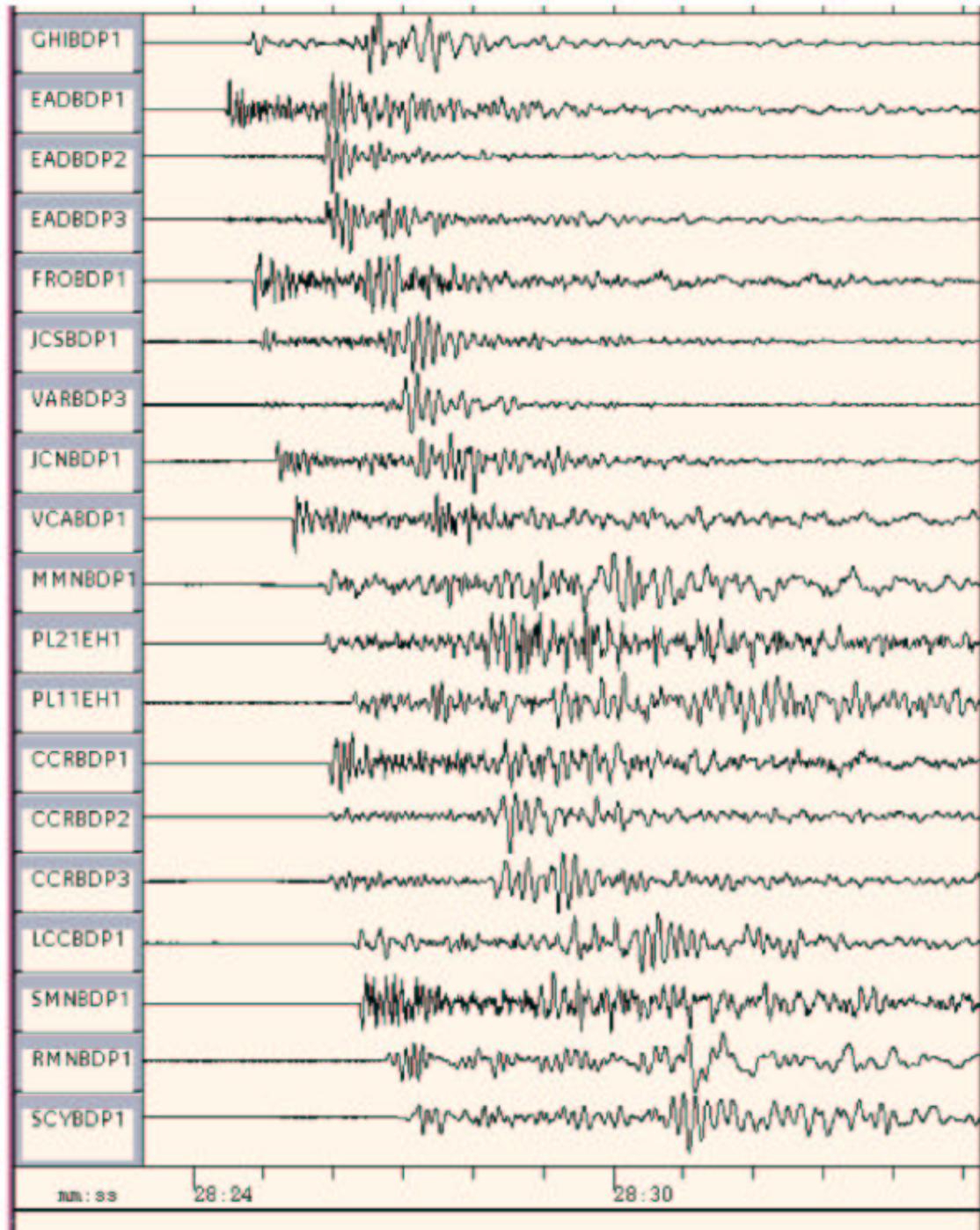
Figure 6.6: Sample HRSN and SAFOD Pilot Hole (PL11 and PL21) waveforms from the Sept. 6, 2002 magnitude 3.9 earthquake occurring some 3-4 km southeast of Parkfield, CA, at a depth of about 9.5 km. Station GHIB is located southeast of the event by about 5 km (top waveform). All other stations locate northwest of the event and are ordered according to their progressively increasing P arrival times. In general only the vertical components of the 3 component sensors are shown. Exceptionally, all three components of the station closest to the event (EADB) and the station closest to planned SAFOD drill site (CCRB) are shown. Horizontal component DP3 has been substituted for the vertical component at VARB due to a recording failure on the VARB vertical for this event. Seismograms are unfiltered and without corrections for sensor response or polarity. PH sensor PL21 is particularly deep ( 1.85 km below surface). The P arrival time of PH sensor PL11 (located at the surface) is approximately 0.39 sec. after that of PL21, so the PL11 waveform has been plotted out of arrival time order to facilitate comparison with PL21.

relative to that at PL21 ( 0.39 sec) can be seen. This indicates that the average P-wave velocity in the top 1.85 km of the crust at the PH site is on the order of 4.7 km/sec which is in general agreement with that observed in tomographic inversion of seismic and active source experiments in the area and with velocities expected for the Salinian composition of the crust penetrated by the PH. The PL21 record also shows some slight clipping. Events in the SAFOD penetration zone are much closer to PL21 than the M3.9 event, but are in general much smaller. However, the ultimate target of the SAFOD drilling is penetration of a site of repeating M2 earthquakes. It is not expected that a M2 close-in to PL21 will also cause it to clip, but an outside possibility for such clipping to occur does exist.

Figure 6.7 illustrates the performance of the HRSN borehole stations for recording teleseismic earthquakes. Shown are records of the August 19, 2002 magnitude 7.7 Fiji Is. deep focus earthquake occurring over 8900 km away from Parkfield. The signal-to-noise in the 0.3-2 Hz band shown is very good, allowing for a variety of waveform analyses for deformation of source characteristics and whole earth structure.

Note the contrast in waveform shape in this frequency band, particularly in the coda, of the MMNB recording. Station MMNB is located directly on the surface trace of the SAF and is known to record Fault Zone Guided Waves for local events. Information on the details of the local deep fault zone structure are also contained in the wave fields of energy generated by distant teleseismic events.

## 5. Future Directions

We are continuing to work at reducing magnitude threshold levels and improving data completeness across the network. Initiation of an automated state-of-health monitoring routine is planned soon and a semi-automated waveform and trigger review scheme (GUI based) is currently under development. These improvements will allow for rapid identification of network outages and problems with station/component specific waveform recording.

Additional efforts underway to increase event detection sensitivity include: 1) refinement of a station specific filtering scheme, 2) refinement of subnet triggering scheme to allow for 2 (instead of 3) station triggering criteria to provide detection of even smaller local earthquakes, 3) incorporation of the pilot hole array into the network triggering scheme to capture the smallest events in the SAFOD drilling area. 4) continue assessment of waveform/spectral character to search for further artificial noise sources at finer scales, and consideration and development for associated fixes.

Monitoring of the systematics of microseismic charac-

teristics, particularly in the SAFOD drilling and target zone, is a primary objective of the HRSN data collection effort. Continued analysis of these data for detailed seismic structure, for similar and characteristic microearthquake systematics, for slip rate evolution, and for determining the source patch size and other characteristics of the SAFOD target(s) and associated earthquakes is also a primary focus that is being pursued in our ongoing research (Chapter 15).

## 6. Acknowledgements

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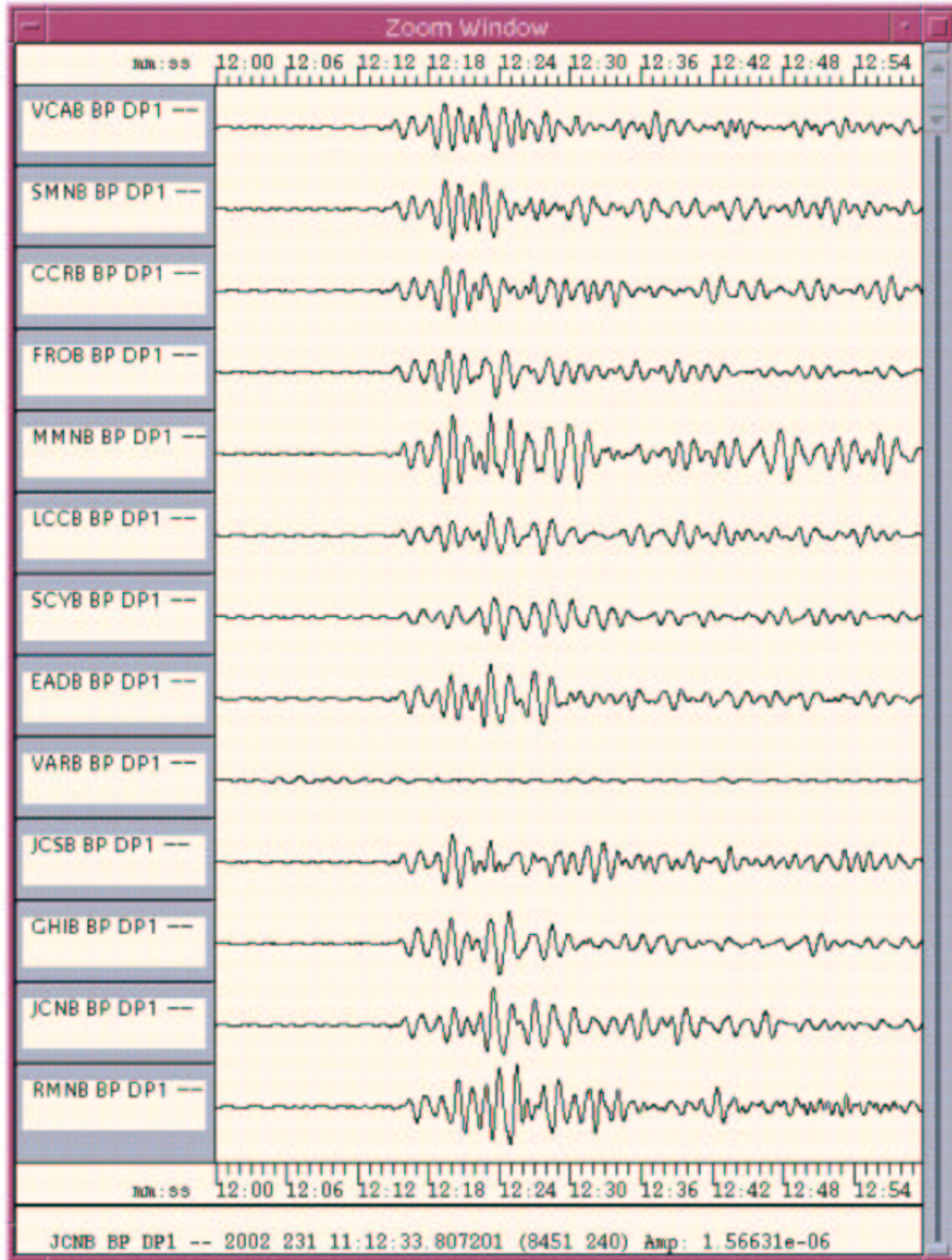
Figure 6.7: Sample 1 minute length seismograms for the 19 August 2002 deep focus Fiji Islands teleseism (11:01 UT, -21.70, -179.51, 580 km deep, M 7.7). Vertical components for the 13, 3-component HRSN borehole stations are shown. The waveforms have been deconvolved to ground velocity, and 0.3-2 Hz bandpass filtered, and plotted using an absolute scale. Station VARB vertical experienced a recording failure during this event. A similar plot for the same earthquake, recorded on the Northern Hayward Fault Network, is show in Figure 5.2.

# Chapter 7

# Parkfield-Hollister Electromagnetic Monitoring Array

## 1. Introduction

There are many reports of anomalous electric and magnetic fields, at frequencies from quasi DC to several 10's of Hertz, and changes in ground resistivity prior to earthquakes. Most reports are devoted to one or another of these phenomena using a variety of measurement configurations and data processing techniques. No such studies are reported using instrumentation capable of measuring all these properties simultanously at a network of sites. It is the objective of this study to determine whether significant changes in resistivity, quasi DC electric fields, or ULF electric and magnetic fields occur before earthquakes in California. In 1995 we installed two well-characterized electric and magnetic field measuring systems at two sites along the San Andreas Fault which are part of the Berkeley Digital Seismic Network. Since then, magnetotelluric (MT) data have been continuously recorded at 40 Hz and 1 Hz and archived at the NCEDC (Table 7.1 and 7.2). At least one set of orthogonal electric dipoles measures the vector horizontal electric field, E, and three orthogonal magnetic sensors measure the vector magnetic field, B. These reference sites, now referred to as electromagnetic (em) observatories, are colocated with seismographic sites so that the field data share the same time base, data acquisition, telemetry and archiving system as the seismometer outputs. Using a robust multiple station MT processing algorithm (*Egbert*, 1997), we have examined the long term stability of single site and interstation transfer functions. Using a precise transfer function obtained from long runs of the array data, we can effectively predict the fields at one site from those measured at another site. Subtracting the predicted fields from the measured fields at a site yields residuals which are more sensitive to anomalous signals local to the site. Residual analysis in both time and frequency is the primary goal of this project.
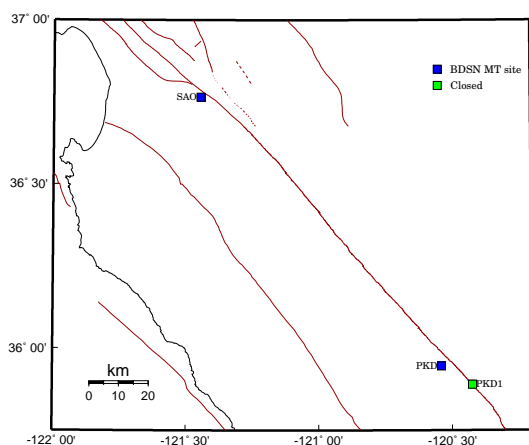


Figure 7.1: Map illustrating the location of operational (filled squares) and closed (grey squares) MT sites in central California.

## 2. MT Overview

The MT observatories are located at Parkfield (PKD1, PKD) 300 km south of the San Francisco Bay Area and Hollister (SAO), halfway between San Francisco and Parkfield (Figure 7.1). In 1995, initial sites were established at PKD1 and SAO, separated by a distance of 150 km, and equipped with three induction coils and two 100 m electric dipoles. PKD1 was established as a temporary seismic site, and when a permanent site (PKD) was found, a third MT observatory was installed in 1999 with three induction coils, two 100 m electric dipoles, and two 200 m electric dipoles. PKD and PKD1 ran in parallel for one month in 1999, and then the MT observatory at PKD1 was closed.

Data at the MT sites are fed to Quanterra data loggers, shared with the collocated BDSN stations, synchronized in time by GPS and sent to the BSL via dedicated communication links.

# 3. Activities in 2001-2002

In the past year, significant energy was directed toward the maintenance of the MT network and toward the establishment of routine data processing.

## 3.1 Station Maintenance

### SAO

SAO experienced problems with the power supplies for the B-field and E-field equipment. The B-field coils and the EFSC box were removed, calibrated, and returned. The voltage regulator circuit of the B-field power supply was replaced.

### PKD

The site at Parkfield continued to have problems with electrodes drying out. Sierra Boyd visited the site several times to "water" the holes and experimented with using bentonite to help retain moisture. The electrodes were pulled in March and the copper-sulfate solution was replaced. In parallel, lead-lead-chloride electrodes were provided by John Booker of the University of Washington. It is hoped that the lead-lead-chloride electrodes will be less sensitive to the lack of moisture in the holes.

### Instrument Responses

As part of the station maintenance, calibrations have been performed on various components of the MT systems. Sierra Boyd is working to ensure that the transfer function information at the NCEDC is correct and current.

## 3.2 Data quality control

During this year, BSL staff worked in collaboration with Gary Egbert to install software developed by him for automated data processing. The software, which is described more fully below, provides the capability of identifying problems and alerting staff.

# 4. Data Processing

A major part of the recent effort at Oregon State University has been to develop user friendly computer codes for routine processing of data from the UCB MT sites. The processing system is based on a graphical user interface, written in MATLAB, which allows the user to download MT data from the NCEDC and complete all routine processing steps (including the multi-site). The program also can be used to plot processing results, multi-channel time series and various simple diagnostics of data quality. Results (including daily estimates of MT impedances, inter-station transfer functions, estimates of noise amplitudes, and summaries of frequency and time domain residual amplitudes) are then automatically archived for statistical analysis and correlation in space and time with cluster events at Parkfield. There is now a daily printout of the signal to noise ratios (SNR) in dB for each channel of the array, Table 7.3. Currently, SNR's below 10 dB are flagged for inspection or repair by the array operators.

Any data in the NCEDC archive can be downloaded, but by default the program gets and processes the most recent unprocessed data. These codes will thus enable more-or-less automatic monitoring of system functionality, and make it easier to maintain a high rate of quality data return. The streamlined processing codes will also make it easier to reprocess existing data with any new schemes that will be implemented in the future. We are presently using the new system to process the backlog of data from the array, and to update analyses of residuals, and of MT impedance stability.

Several procedures for the residual analysis (the goal of the em array) have been developed: one uses a simple time-domain regression operator to estimate residuals in a moving time window. This algorithm is fast and provides a rapid method to scan incoming data for anomalies. We have tested this process on selected segments of data. No anomalous signals were detected, but there were no earthquakes during this interval.

Another approach is a frequency domain analysis using multiple station techniques (*Egbert*, 1977) which makes optimal use of data from all sites to estimate stable and reliable transfer functions. The multi-site analysis has also proven to be very useful for better understanding of signal and noise, and for separating coherent signals of differing spatial scales (Figure 7.2). For example, *Egbert et al.* (2000) used a multiple station analysis to show that the transfer function between SAO and PKD1 is systematically affected by both the DC train system in the Bay Area (BART) and by the non-uniformity of the natural fields in the Pc3 band (Figure 7.3). These results demonstrated that cultural noise sources can extend their effect over surprisingly large areas, and that at the same time natural ionospheric sources may exhibit significant spatial complexity. Because of this added spatial complexity, multiple sites are required for complete cancellation of the background (non-tectonic) em noise. Ideally three stations should be used to avoid bias errors in the transfer function estimates and to maintain better control over cultural noise.

Predictions based on data from at least three sites will significantly improve our ability to detect anomalous signals. Source complications, as well as local incoherent noise sources, are highly variable in time (e.g., Figure 7.3), making it a challenging task to verify that apparently anomalous signals truly originate in the earth. Thorough calibration and understanding of both local and distant noise sources is essential. This critical step has now been accomplished for the UCB array (*Egbert et al.*, 2000; *Eisel and Egbert*, 2001). When a major Park-

field event does occur we will be in a very good position to detect and identify anomalous em emissions (if there are any) and to avoid the ambiguity of interpretation that has plagued much of the past search for em precursors.

So far we have focused on the frequency domain approach to study residuals. This analysis has revealed significant diurnal variations in the residual distributions. With a two site array, residuals are smallest between the hours of 0-4 am, making this a particularly good time to look for anomalous signals. Comparison of the temporal distribution of unusually large magnetic residuals to local earthquake catalogs has so far revealed no clear associations, but there have been few earthquakes of significant magnitude in the time period studied. *Karakelian et al.* (2000) analyzed data from some of their sites and ours and suggest that there was anomalous activity before the San Juan Bautista earthquake, but we have not been able to verify this.

The MT stations at PKD and SAO can also be used to monitor resistivity changes prior to earthquakes. Unlike the UC Riverside telluric array, the MT impedance can yield depth information because the depth of penetration of the em waves increases with period. Seasonal changes caused by precipitation would presumably be shallow and affect primarily the shorter periods, while deeper changes would be seen also at longer periods. The amplitude of the MT impedance may fluctuate at all periods in response to shallow changes (the so-called "static" shift problem), but the phase of the response is set by more regional structure at longer periods. Thus, variations in phase should be a sensitive indicator of resistivity variations at seismogenic depths ($\sim$10 km). *Eisel and Egbert* (2001) made a study of the stability of the MT impedances at PKD1. Typical deviations of estimates based on a single day of data differed from the long term average transfer function by 2-3% for T < 300s and increasing to about 10% for T=2000s. Variations between contiguous days were nearly random, so significantly smaller variability can be obtained by longer averaging times. There is some evidence from this analysis for a slow variation of about 1% in impedance amplitude when an 11 day average is applied. Relative resistivity variations are nearly frequency independent, appear anti-correlated between the x-y and y-x modes, and are larger than variations in phase. These features together are suggestive of temporal variations in near-surface static distortion. Although it is difficult to make a definitive statement on the basis of the data analyzed so far, there does not appear to be any seasonal component to these variations, as might be expected if they were due to near surface hydrology.

| Sensor | Channel | Rate (sps) | Mode | FIR |
|--------|---------|-----------|------|-----|
| Magnetic | VT? | 0.1 | C | Ac |
| Magnetic | LT? | 1.0 | C | Ac |
| Magnetic | BT? | 40.0 | C | Ac |
| Electric | VQ? | 0.1 | C | Ac |
| Electric | LQ? | 1.0 | C | Ac |
| Electric | BQ? | 40.0 | C | Ac |

Table 7.2: Typical data streams acquired at each MT site, with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous; T triggered; Ac acausal.

| Station | Channel | T=30S | T=100S | T=300S |
|---------|---------|-------|--------|--------|
| PKD | Hx | 26 | 25 | 26 |
| PKD | Hy | 23 | 22 | 24 |
| PKD | Hx | 18 | 17 | 15 |
| PKD | Ex1 | 16 | 16 | 18 |
| PKD* | Ey1 | 9 | 10 | 11 |
| PKD | Ex2 | 23 | 23 | 26 |
| PKD | Ey2 | 21 | 23 | 25 |
| SAO | Hx | 21 | 21 | 23 |
| SAO | Hy | 21 | 20 | 24 |
| SAO | Hz | 15 | 12 | 12 |
| SAO | Ex | 22 | 21 | 22 |
| SAO | Ey | 21 | 21 | 20 |

Table 7.3: SNR at selected periods (dB): Bad channels indicated *

| Site | Net | Latitude | Longitude | Elev (m) | Date | Location |
|------|-----|----------|-----------|----------|------|----------|
| PKD  | BK  | 35.945171 | -120.541603 | 583 | 1999/02/05 - | Bear Valley Ranch, Parkfield |
| PKD1 | BK  | 35.8894 | -120.426109 | 431.6 | 1995/06/06 - 1999/03/08 | Haliburton House, Parkfield |
| SAO  | BK  | 36.76403 | -121.44722 | 317.2 | 1995/08/15 - | San Andreas Obs., Hollister |

Table 7.1: Sites of MT observatories
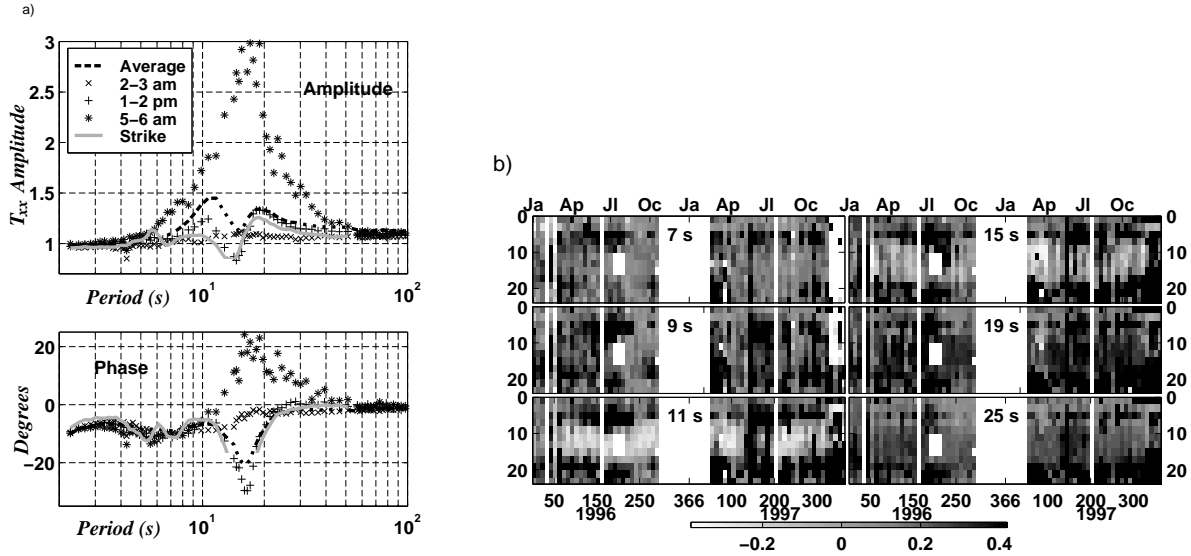


Figure 7.3: (a) Amplitude and phase of the Hx/Hx transfer function (TF) between PKD1 and SAO. Curves marked by symbols correspond to TFs estimated for different local times, as indicated in the legend. The heavy dashed line is the TF computed from all data (days 140-199, 1997), and the heavy grey solid line is the TF computed from the data collected during a strike by BART workers (days 150-156, 1997; see *Egbert et al.* (2000)). For periods outside of the band plotted, TFs computed for different data subsets are in close agreement. (b) Variations in the real part of the Hx/Hx TF as a function of local time and time of year, for data grouped into 10 day-long 2 hour bands.

a)



b)

## 6.   References

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Figure 7.2: (a) Eigenvalues of the scaled Spectral Density Matrix (SDM) for the three site PKD1/PKD/SAO array, computed following the methods described in *Egbert* (1997). Briefly, cross-products of Fourier coefficients computed from short time segments of all 17 data channels are averaged for the 30 days. (b) The magnitude of incoherent noise power is estimated for each data channel, and these are used to non-dimensionalize the SDM. Eigenvalues of the 17x17 scaled SDM then given signal-to-noise (power) ratios of independent coherent EM sources. For idealized quasi-uniform MT sources, there should be only two eigenvalues significantly above the 0 dB noise level. Additional large eigenvalues, as seen here from 10-300 s, are a clear indication of "coherent noise", or temporally varying complications in source geometry. For the two dominant eigenvectors, the horizontal magnetic components are roughly uniform across the array, consistent with the usual MT assumptions. Eigenvectors three and four are dominated by gradients in the EM fields.

# Chapter 8

# Bay Area Regional Deformation Network

## 1. Introduction

The Bay Area Regional Deformation (BARD) network of continuously operating Global Positioning System (GPS) receivers monitors crustal deformation in the San Francisco Bay area ("Bay Area") and northern California (*Murray et al.,* 1998a). It is a cooperative effort of the BSL, the USGS, and several other academic, commercial, and governmental institutions. Started by the USGS in 1991 with 2 stations spanning the Hayward fault (*King et al.,* 1995), BARD now includes 67 permanent stations (Figure 8.1) and will expand to about ~75 stations by July 2003. 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 (SAF) system in the Bay Area to assess seismic hazards; 3) to monitor hazardous faults and volcanoes for emergency response management; and 4) to provide 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.

BARD currently includes 67 continuously operating stations, 34 in the Bay Area and northern California (Table 8.1), 15 near Parkfield, along the central San Andreas fault, and 18 near the Long Valley caldera near Mammoth (Table 8.2). The BSL maintains 21 stations (including 2 with equipment provided by Lawrence Livermore National Laboratory (LLNL) and UC Santa Cruz). Other stations are maintained by the USGS (Menlo Park and Cascade Volcano Observatory), LLNL, Stanford University, UC Davis, UC Santa Cruz, and East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, and the Jet Propulsion Laboratory. Many of these stations are part of larger networks devoted to real-time navigation, orbit determination, and crustal deformation.

Between 1993 and 1996, the BSL acquired 5 Ashtech Z-12 receivers from UC Berkeley and private (EPRI) fund-

ing, which together with 2 USGS receivers, formed the nucleus of the initial BARD network. Since 1996, the BSL has acquired additional Ashtech Z-12 receivers with Dorne-Margolin design choke ring antennas: 13 in 1996 from a combination of federal (NSF), state (CLC), and private (EPRI) funding, 4 in 2000 from USGS funding, and 7 in 2001 from NSF funding. Most of these receivers have been installed to enhance continuous strain measurements in the Bay Area and to consolidate the regional geodetic network. The network includes several profiles between the Farallon Islands and the Sierra Nevada in order to better characterize the larger scale deformation field in northern California (Figure 8.1). Six more of the BSL receivers will be installed next year, 2 along the southern Hayward fault, and 4 as part of the NSF-funded mini-PBO project establishing collocated GPS/seismometer/borehole strainmeter observatories in the Bay Area (see Chapter 9).

In 1996, researchers from the BSL, the USGS, Stanford University, LLNL, UC Davis, and UC Santa Cruz formed a consortium of institutions studying 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. This strategy includes the continued development of the network of continuous GPS receivers, the development and maintenance of a pool of GPS receivers for survey-mode operations that may be deployed in semi-permanent mode in the Bay Area when not otherwise in use, archiving of all data at the NCEDC, and development of a coordinated data analysis facility that will process permanent, semi-permanent, and survey data.

Today, raw and Rinex data files from the BSL stations and the other stations run by BARD collaborators are archived at the BSL/USGS Northern California Earthquake Data Center data archive maintained at the BSL (*Romanowicz et al.,* 1994). The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 2 hours of collection, to all BARD participants
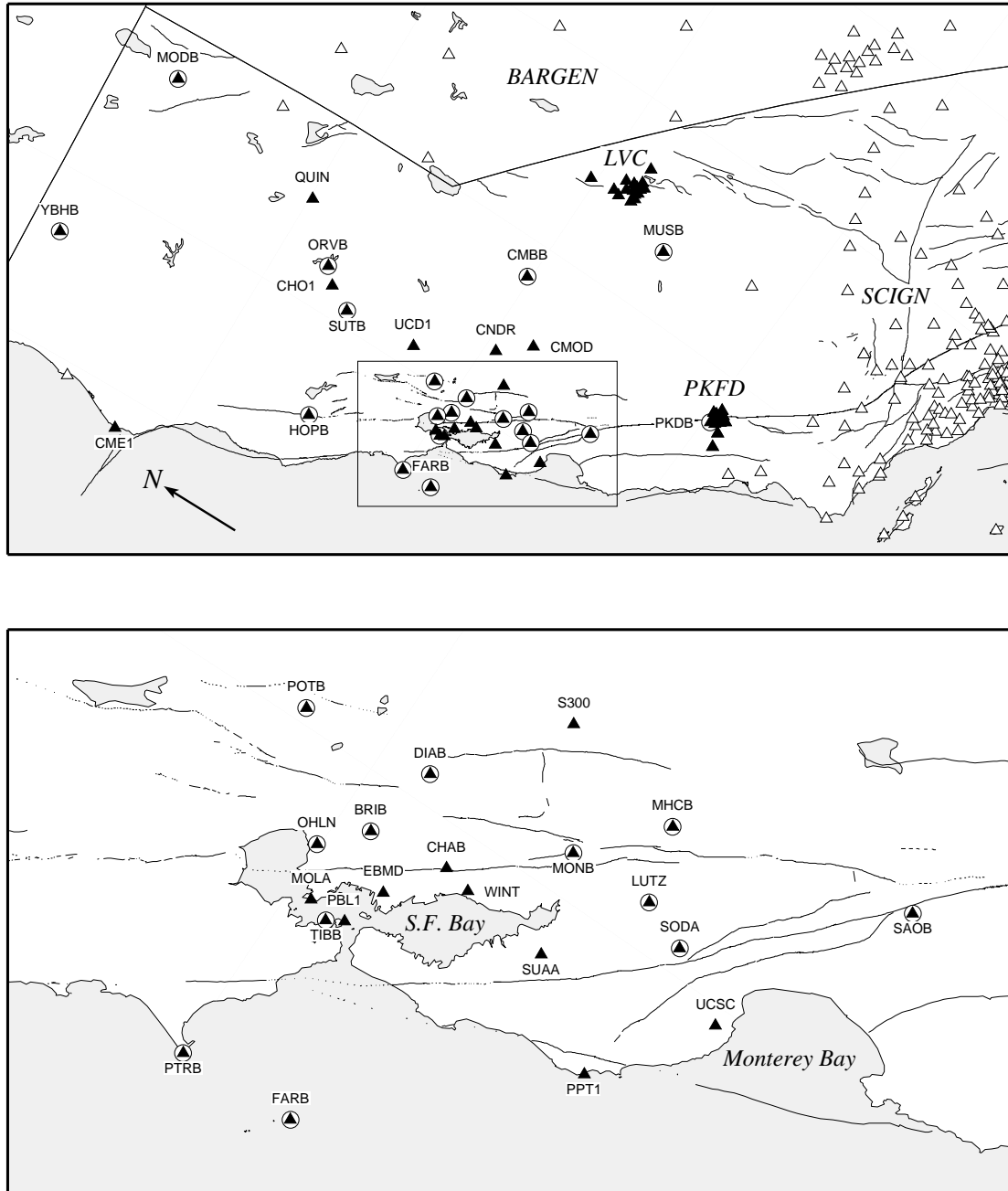
Figure 8.1: Operational BARD stations (solid triangles) in northern California (top) and in the San Francisco Bay area (bottom). The oblique Mercator projection is about the NUVEL-1 Pacific–North America Euler pole so that expected relative plate motion is parallel to the horizontal. Circled stations use continuous telemetry. The 18 station Long Valley Caldera (LVC) network and 15 station Parkfield (PKFD) networks are also part of BARD. Other nearby networks (open triangles) include: Basin and Range (BARGEN), and Southern California Integrated GPS Network (SCIGN).

| Code | Latitude | Longitude | Start | Receiver | Maint. | Telem. | Location |
|------|----------|-----------|-------|----------|--------|--------|----------|
| BRIB | 37.91940 | -122.15255 | 1993.58 | A-Z12 | BSL | FR | Briones Reservation, Orinda |
| CMBB | 38.03418 | -120.38604 | 1993.92 | A-Z12 | BSL | FR | Columbia College, Columbia |
| DIAB | 37.87858 | -121.91563 | 1998.33 | A-Z12 | BSL | FR | Mt. Diablo |
| FARB | 37.69721 | -123.00076 | 1994.00 | A-Z12 | BSL | R-FR/R | Farallon Island |
| HOPB | 38.99518 | -123.07472 | 1995.58 | A-Z12 | BSL | FR | Hopland Field Stat., Hopland |
| LUTZ | 37.28685 | -121.86522 | 1996.33 | A-Z12 | BSL | FR | SCC Comm., Santa Clara |
| MHCB | 37.34153 | -121.64258 | 1996.33 | A-Z12 | BSL | FR | Lick Obs., Mt. Hamilton |
| MODB | 41.90233 | -120.30283 | 1999.83 | A-Z12 | BSL | NSN | Modoc Plateau |
| MOLA | 37.94657 | -122.41992 | 1993.75 | T-SSE | BSL | | Pt. Molate, Richmond |
| MONB | 37.49892 | -121.87131 | 1998.50 | A-Z12 | BSL | FR | Monument Peak, Milpitas |
| MUSB | 37.16994 | -119.30935 | 1997.83 | A-Z12 | BSL | R-Mi-FR | Musick Mt. |
| OHLN | 38.00742 | -122.27371 | 2001.83 | A-Z12 | BSL | FR | Ohlone Park, Hercules |
| ORVB | 39.55463 | -121.50029 | 1996.83 | A-Z12 | BSL | FR | Oroville |
| PKDB | 35.94524 | -120.54155 | 1996.67 | A-Z12 | BSL | FR | Bear Valley Ranch, Parkfield |
| POTB | 38.20258 | -121.95560 | 1998.92 | A-Z12 | BSL | FR | Potrero Hill, Fairfield |
| PTRB | 37.99640 | -123.01490 | 1998.58 | A-Z12 | BSL | R-FR | Point Reyes Lighthouse |
| SAOB | 36.76530 | -121.44718 | 1997.58 | A-Z12 | BSL | FR | San Andreas Obs., Hollister |
| SODB | 37.16640 | -121.92552 | 1996.33 | A-Z12 | BSL | R-FR | Soda Springs, Los Gatos |
| SUTB | 39.20584 | -121.82060 | 1997.33 | A-Z12 | BSL | R-FR | Sutter Buttes |
| TIBB | 37.89087 | -122.44760 | 1994.42 | A-Z12 | BSL | R | Tiburon |
| YBHB | 41.73166 | -122.71073 | 1996.75 | A-Z12 | BSL | FR | Yreka Blue Horn Mine, Yreka |
| CHAB | 37.72412 | -122.11931 | 1992.00 | A-Z12 | USGS | | Chabot, San Leandro |
| WINT | 37.65264 | -122.14056 | 1992.00 | A-Z12 | USGS | | Winton, Hayward |
| EBMD | 37.81501 | -122.28380 | 1999.18 | T-SSi | EBMUD | | EBMUD, Oakland |
| QUIN | 39.97455 | -120.94443 | 1992.68 | Rogue | JPL | | Quincy |
| S300 | 37.66642 | -121.55815 | 1998.48 | T-SSi | LLNL | | Site 300, Livermore |
| CHO1 | 39.43264 | -121.66496 | 1999.50 | A-Z12 | NGS | | Chico |
| CME1 | 40.44177 | -124.39633 | 1995.74 | A-Z12 | NGS | | Cape Mendocino |
| CMOD | 37.64130 | -121.99997 | 2000.76 | T-SSi | City | | Modesto |
| CNDR | 37.89641 | -121.27849 | 1999.27 | A-Z12 | NGS | | Condor, Stockton |
| PBL1 | 37.85306 | -122.41944 | 1995.50 | A-Z12 | NGS | | Point Blunt, Angel Island |
| PPT1 | 37.18167 | -122.39333 | 1996.00 | A-Z12 | NGS | | Pigeon Point |
| SUAA | 37.42691 | -122.17328 | 1994.30 | A-Z12 | SU | | Stanford University |
| UCD1 | 38.53624 | -121.75123 | 1996.38 | T-SSi | UCD | | UC Davis |
| UCSC | 36.99279 | -122.05219 | 2000.31 | T-SSi | UCSC | | UC Santa Cruz |

Table 8.1: Currently operating stations of the BARD GPS network maintained by the BSL or by other agencies except in the Parkfield and Long Valley caldera regions. Other agencies include: EBMUD = East Bay Mun. Util. Dist., UCD = UC Davis, SU = Stanford Univ., UCSC = UC Santa Cruz, City = City of Modesto (see also Table 1.1). Receivers: A = Ashtech, T = Trimble. See Table 4.2 for telemetry codes and for BSL sites collocated with seismic stations. Data from other agencies retrieved or pushed by ftp or from the web.

and other members of the GPS community through Internet, both by anonymous ftp and by the World Wide Web (http://quake.geo.berkeley.edu/bard/).

Data and ancillary information about BARD stations 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 NCEDC also retrieves data from other GPS archives, such as at SIO, JPL, and NGS, in order to provide a complete archive of all high-precision continuous GPS measurements collected in northern California.

Many of the BARD sites are classified as CORS stations by the NGS, which are used as reference stations by the surveying community. All continuous stations operating in July 1998 and May 2000 were included in a statewide adjustments of WGS84 coordinates for this purpose. Members of the BARD project regularly discuss these and other common issues with the surveying community at meetings of the Northern California GPS Users Group and the California Spatial Reference Center.

| Code | Latitude | Longitude | Start | Receiver | Maint. | Location |
|---|---|---|---|---|---|---|
| CAND | 35.93935 | -120.43370 | 1999.33 | A-Z12 | USGS | Cann, Parkfield |
| CARH | 35.88838 | -120.43082 | 2001.58 | A-Z12 | USGS | Carr Hill 2, Parkfield |
| CARR | 35.88835 | -120.43084 | 1989.00 | A-Z12 | JPL | Carr Hill, Parkfield |
| CRBT | 35.79161 | -120.75075 | 2001.67 | A-Z12 | USGS | Camp Roberts, Parkfield |
| HOGS | 35.86671 | -120.47949 | 2001.50 | A-Z12 | USGS | Hogs, Parkfield |
| HUNT | 35.88081 | -120.40238 | 2001.58 | A-Z12 | USGS | Hunt, Parkfield |
| LAND | 35.89979 | -120.47328 | 1999.33 | A-Z12 | USGS | Lang, Parkfield |
| LOWS | 35.82871 | -120.59428 | 2001.58 | A-Z12 | USGS | Lowes, Parkfield |
| MASW | 35.83260 | -120.44306 | 2001.58 | A-Z12 | USGS | Mason West, Parkfield |
| MIDA | 35.92191 | -120.45883 | 1999.75 | A-Z12 | USGS | Mida, Parkfield |
| MNMC | 35.96947 | -120.43405 | 2001.58 | A-Z12 | USGS | Mine Mt., Parkfield |
| POMM | 35.91991 | -120.47843 | 1999.75 | A-Z12 | USGS | Pomm, Parkfield |
| RNCH | 35.89999 | -120.52482 | 2001.58 | A-Z12 | USGS | Ranchita, Parkfield |
| TBLP | 35.91741 | -120.36034 | 2001.67 | A-Z12 | USGS | Table, Parkfield |
| BALD | 37.78330 | -118.90130 | 1999.67 | A-ZFX | CVO | Bald Mt., LVC |
| CA99 | 37.64460 | -118.89670 | 1999.67 | A-ZFX | CVO | Casa 1999, LVC |
| CASA | 37.64464 | -118.89666 | 1993.00 | Rogue | JPL | Casa Diablo, LVC |
| DDMN | 37.74430 | -118.98120 | 1999.67 | A-ZFX | CVO | Deadman Creek, LVC |
| DECH | 38.05150 | -119.09060 | 2001.58 | A-ZFX | CVO | Dechambeau Ranch, LVC |
| HOTK | 37.65860 | -118.82130 | 2001.67 | A-Z12 | CVO | Hot Creek, LVC |
| JNPR | 37.77170 | -119.08470 | 1997.81 | A-Z12 | USGS | Juniper, LVC |
| KNOL | 37.65912 | -118.97917 | 1998.58 | A-ZFX | CVO | Knolls, LVC |
| KRAC | 37.71330 | -118.88050 | 2001.67 | A-Z12 | CVO | Krakatoa-USGS, LVC |
| KRAK | 37.71313 | -118.88114 | 1994.73 | Rogue | JPL | Krakatoa, LVC |
| LINC | 37.63719 | -119.01729 | 1998.67 | A-Z12 | CVO | Lincoln, LVC |
| MINS | 37.65376 | -119.06090 | 1995.92 | A-Z12 | USGS | Minaret Summit, LVC |
| MWTP | 37.64052 | -118.94473 | 1998.58 | A-ZFX | CVO | Mammoth Water Treat Plant, LVC |
| PMTN | 37.83130 | -119.05690 | 1999.67 | A-Z12 | CVO | Panorama Mt., LVC |
| RDOM | 37.67707 | -118.89794 | 1998.58 | A-ZFX | CVO | Resurgent Dome, LVC |
| SAWC | 37.68990 | -118.95310 | 2000.65 | A-ZFX | CVO | Saw, LVC |
| TILC | 37.61890 | -118.86280 | 2000.65 | A-Z12 | CVO | Tilla, LVC |
| WATC | 37.66440 | -118.65390 | 2001.67 | A-Z12 | CVO | Waterson, LVC |

Table 8.2: Currently operating stations of the BARD GPS network maintained by other agencies in the Parkfield and Long Valley caldera regions. Other agencies include: CVO = USGS Cascade Volcano Observatory (see also Table 1.1). Receivers: A = Ashtech. Data from other agencies retrieved or pushed by ftp or from the web.

In the remainder of this section, we describe the standard BARD station and some of the BARD-related activities the BSL has performed over the last year, including maintenance to existing stations, installation of a new station and an experimental single-frequency receiver profile, improvement in processing methods, and analysis of the data to estimate deformation signals monitored by the network.

## 2.  BARD Stations

A BSL continuous GPS station uses a low-multipath choke-ring antenna mounted to a reinforced concrete pillar approximately 0.5 meter above local ground level. The reinforcing steel bars of the pillar are drilled and cemented into rock outcrop to improve long-term monument stability. It uses a low-loss antenna cable to minimize signal degradation on the longer cable setups that normally would require signal amplification. Low-voltage cutoff devices are installed to improve receiver performance following power outages. The Ashtech Z-12 receiver is programmed to record data once every 30 seconds, observing up to 12 satellites simultaneously at elevations down to the horizon.

Tests performed by UNAVCO on low antenna mounts revealed that estimates of tropospheric water vapor from the GPS data are strongly correlated with signal multipath errors, which can degrade the precision of the vertical position estimates. Most of the BSL GPS stations use monuments that elevate the antennas 0.5–1.0 m above the ground surface, which helps to minimize the correlations between multipath and tropospheric parameters.

The stations are equipped with SCIGN-designed hemispherical domes. Domes cover the antennas to provide security and protection from the weather and other natural phenomenon. The SCIGN dome is designed for the Dorne-Margolin antennas and minimizes differential radio propagation delays by being hemispherical about the phase center and uniform in thickness at the 0.1 mm level. It is also very resistant to damage and, in its tall form combined with the SCIGN-designed antenna adapter, can completely cover the dome and cable connections for added protection. All new stations use the adapters and tall domes. Some of the older stations in well protected areas use the short domes.

Data from all BSL-maintained stations are collected at 30-second intervals and transmitted continuously over serial connections (Table 8.1). Station TIBB uses a direct radio link to Berkeley, and MODB uses VSAT satellite telemetry. The 18 stations use frame relay technology, either alone or in combination with radio telemetry. Twelve GPS stations are collocated with broadband seismometers and Quanterra data collectors (Table 4.2). With the support of IRIS we developed software that converts continuous GPS data to MiniSEED opaque blockettes, which can be stored and retrieved from the Quanterra data loggers (*Perin et al.,* 1998). The MiniSEED approach provides more robust data recovery from onsite backup on the Quanterra disks following telemetry outages. Our comparisons also show the loss of individual records is fewer when using the Quanterra MiniSEED rather than direct serial method due to the superior short-term data buffer in the Quanterra. Data from the 12 collocated stations plus SUTB are retrieved in this manner.

# 3. 2001-2002 Activities

During July 2001–June 2002, we performed maintenance on existing BARD stations, installed a new station, and prepared for new stations near the Hayward fault, on the San Francisco peninsula, and north Bay area regions.

## 3.1 Station Maintenance

In March 2002, "copper-miners" took advantage of of the poor security at the decommissioned Point Molates naval facility to fell the power poles and remove high tension copper power lines that were used by the MOLA station. The property has been put aside for environmental cleanup before the ownership is transferred from the Navy to the City of Richmond. Due to the status of the property, the high costs to reestablish power, and the unsecured nature of the area, the station was removed from continuous GPS service. The monument and enclosure were left intact and the site is being be periodically reoccupied, approximately 2–3 days per month, in a semi-permanent mode.

In May 2002, forced entry in the building housing the GPS equipment at SAOB resulted in theft of GPS receiver and damage to building and telemetry system. We reinforced the plywood building walls with a layer of wire mesh followed by a surface layer of plywood secured with screws and liquid adhesive. Inside the building, the GPS receiver and short-haul modems where replaced and stored within a double locked large metal "Hoffman" box.

Also in May 2002, the receiver and Freewave radio at Sutter Buttes (SUTB) were replaced due to a data outage following an electrical storm and possible lightning strike. The site is located on top of the South Butte, 2000 feet above the Central Valley.

## 3.2 New Installations

### Mini-PBO sites

In the summer and fall of 2001, we helped to do site reconnaissance, permitting, and installations for the NSF-funded mini-PBO project establishing collocated GPS/seismometer/borehole strainmeter observatories in the Bay Area. Boreholes were drilled to around 200 m at 4 sites, and strainmeter and seismometer instruments were installed in 3 of the boreholes (the fourth proved problematic and could not be completed until August 2002). Due to delays by utility companies in establishing power and telemetry, only the station OHLN at Ohlone Park in Hercules, about 5 km west of the northern Hayward fault, became fully operational. The GPS antenna is mounted on the top of the 6" borehole casing, in an experimental approach to obtain a stable, compact monument. GPS data from OHLN is now publicly available from the NCEDC, and included in the automated BARD processing for hourly and daily site positions. For more details about the OHLN station installation, and the other mini-PBO sites, see Chapter 9).

### L1-system Profile

The BSL staff is evaluating the performance of the UNAVCO-designed L1 system in an urban setting. This single-frequency receiver is relatively inexpensive but is less accurate than dual-frequency receiver systems that can completely eliminate first-order ionospheric effects. Hence we expect the L1 system to be most useful for short baseline measurements where ionospheric effects tend to cancel due to similar propagation paths. The systems are self-contained, using solar power and integrated radio modems. During 1999, the BSL borrowed 2 receivers and a master radio from UNAVCO to perform the evaluation, but persistent hardware and software problems limited progress on this project. UNAVCO subsequently resolved many of the problems and in summer 2000, we received new, improved equipment and software for 4 systems and a master radio.

During 2000 and 2001, we completed permitting at 4

Figure 8.2: Location of L1-system (open triangles) and BARD (closed circles) stations. BSL, just southwest of the Hayward fault, is the location of the Berkeley Seismological Laboratory, where data from the 4 L1-system receivers northeast of the Hayward are telemetered.



Figure 8.3: L1 system installation at GRIZ. This autonomous system uses solar panels (mounted in back) and Freewave radios (with Yagi antenna mounded on pole below GPS antenna). GPS receiver, radio, solar power regulators, and backup batteries are in the electronics box mounted in front.

sites on a 10-km profile extending normal to the Hayward fault between the UC Berkeley campus and the permanent BRIB site (Fig. 8.2). This profile, complemented by BRIB and EBMD to the west of the fault, will be most sensitive to variations in locking at 2-8 km depth. We expect that these systems will provide useful constraints on relative displacements near the Hayward fault in 3–5 years, and should help to resolve variations in creeping and locked portions of the fault (e.g., *Bürgmann et al,* 2000).

Three sites are located on East Bay Municipal Utilities District (EBMUD) property. The station BDAM is located just east of the Briones Dam and a few km west of the Briones (BRIB) continuous BARD station. Wildcat (WLDC) is located near the San Pablo Reservoir, and VOLM is located on the ridge of the East Bay Hills close to Volmer Peak. The fourth site, Grizzly Flat (GRIZ), is located on East Bay Regional Park property just west of Grizzly Peak. Finding suitable stations with line-of-sight telemetry across the East Bay Hills proved challenging. Data from WLDC must pass through all the other stations, with its relay path being (in order) BDAM, VOLM, GRIZ, a repeater on the UC Berkeley Space Sciences Building, and then finally the master radio on the roof of McCone Hall where the BSL is located

on campus.

In April 2002, we installed the L1 Profile with assistance from two engineers from UNAVCO. We used a large gas powered hand drill to bore a 2" diameter, 18" deep hole into bedrock at the BDAM and VOLM sites, and cemented in a galvanized pipe using expansive grout. GRIZ and WLDC are located in areas where we could not easily access bedrock. GRIZ is located on top of a small plateau covered in volcanic deposits that have weathered to clay. Bedrock was observed nearby uphill of the WLDC site, but could not be used due to telemetry constraints. At both of these sites a subsurface concrete pier was constructed, laced with chicken wire to reduce cement fracturing during drying, and anchored by steel rebar pounded into the ground at several angles.

The electronics, including gps/radio unit, battery and solar power manager, are securely stored within a medium-sized Hoffman box, or locking metal enclosure, attached to pipe. Whenever possible access to the in-

side of box is necessary to remove bolts attaching the box itself. GPS antenna is mounted on a fiberglass rod attached to top of pipe. All loose cables are zip-tied in place and all stainless steel bolts are epoxied to discourage theft. A typical site, with a Yagi antenna for communications, is shown in Figure 8.3.

Since April, we have been assessing the data quality and processing the data to estimate daily site positions. Problems with telemetry outages at WLDC during the early morning, pre-dawn hours, were found to be due to a faulty battery, and were corrected when we installed new batteries at all the sites. GRIZ currently is experiencing intermittent data outages which were not solved by the new battery or by replacing the receiver/radio unit. We are currently investigating possible problems with the solar power regulator. We are also in the process of obtaining 2 additional systems from UNAVCO that will be installed on the roofs of the Space Sciences and McCone Hall buildings, which will make the profile cross the Hayward fault and allow direct measurement of surface creep in this region.

We are developing techniques to process the data using the GAMIT/GLOBK analysis package. We corrected software provided by UNAVCO to synchronize the phase, pseudorange, and clock offset observables, which allows the data to be cleaned in an automatic fashion. Preliminary results suggest that repeatabilities of 1–2 mm in daily horizontal positions on the shortest (several km) baselines can be achieved (Figure 8.4), but these degrade to 3–4 mm on the longer (10 km) baselines. We are investigating ways to simultaneously process the dual-frequency data from nearby BARD stations (e.g., BRIB, OHLN), with the single-frequency L1 data to improve these results. Currently data from second frequency on the BARD stations is not used, which degrades the definition of the local reference frame and repeatability of the baselines.
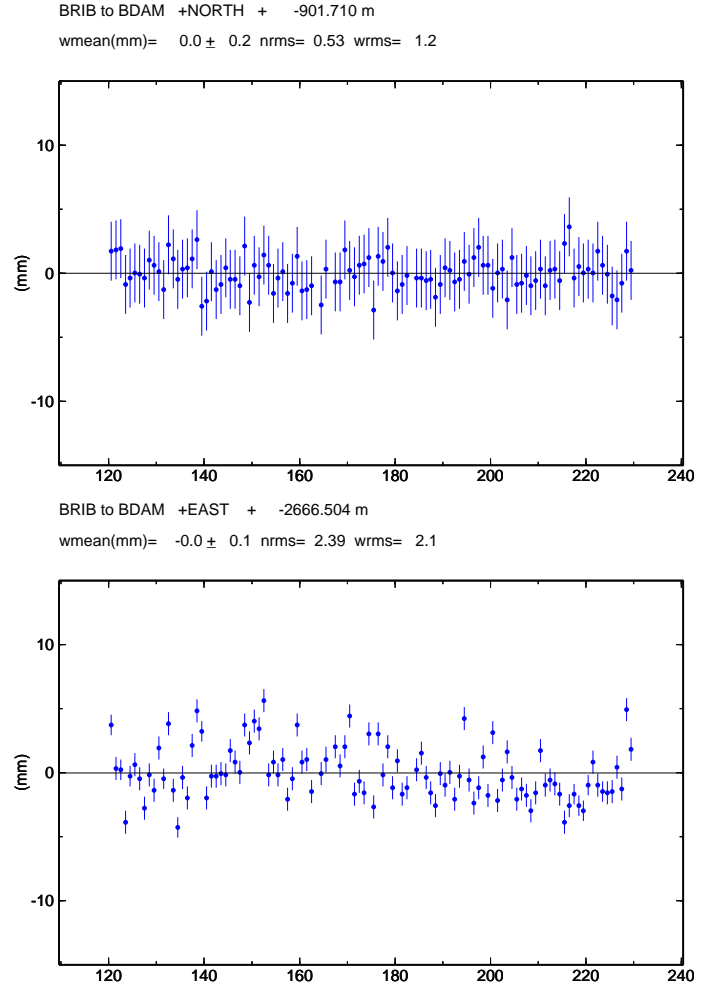


Figure 8.4: Daily estimates of the north and east components of the BRIB to BDAM 3-km baseline. Daily repeatabilities are about 1 mm in north, and 2 mm in east.

# 4.  Data Analysis and Results

The data from the BARD sites generally are of high quality and measure relative horizontal positions at the 2–4 mm level. The 24-hour RINEX data files are processed daily with an automated system using high-precision IGS orbits. Final IGS orbits, available within 7–10 days of the end of a GPS week, are used for final solutions. Preliminary solutions for network integrity checks and rapid fault monitoring are also estimated from Predicted IGS orbits (available on the same day) and from Rapid IGS orbits (available within 1 day). Data from 5 primary IGS fiducial sites located in North America and Hawaii are included in the solutions to help define a global reference frame. Average station coordinates are estimated from 24 hours of observations using the GAMIT software developed at MIT and SIO, and the solutions are output with weakly constrained station coordinates and satellite state vectors.

Processing of data from the BARD and other nearby networks is split into 7 geographical subregions: the Bay Area, northern California, Long Valley caldera, Parkfield, southern and northern Pacific Northwest, and the Basin and Range Province. Each subnet includes the 5 IGS stations and 3 stations in common with another subnet to help tie the subnets together. The weakly constrained solutions are combined using the GLOBK software developed at MIT, which uses Kalman filter techniques and allows tight constraints to be imposed a posteriori. This helps to ensure a self-consistent reference frame for the final combined solution. The subnet solutions for each day are combined assuming a common orbit to estimate weakly constrained coordinate-only solutions. These daily coordinate-only solutions are then combined
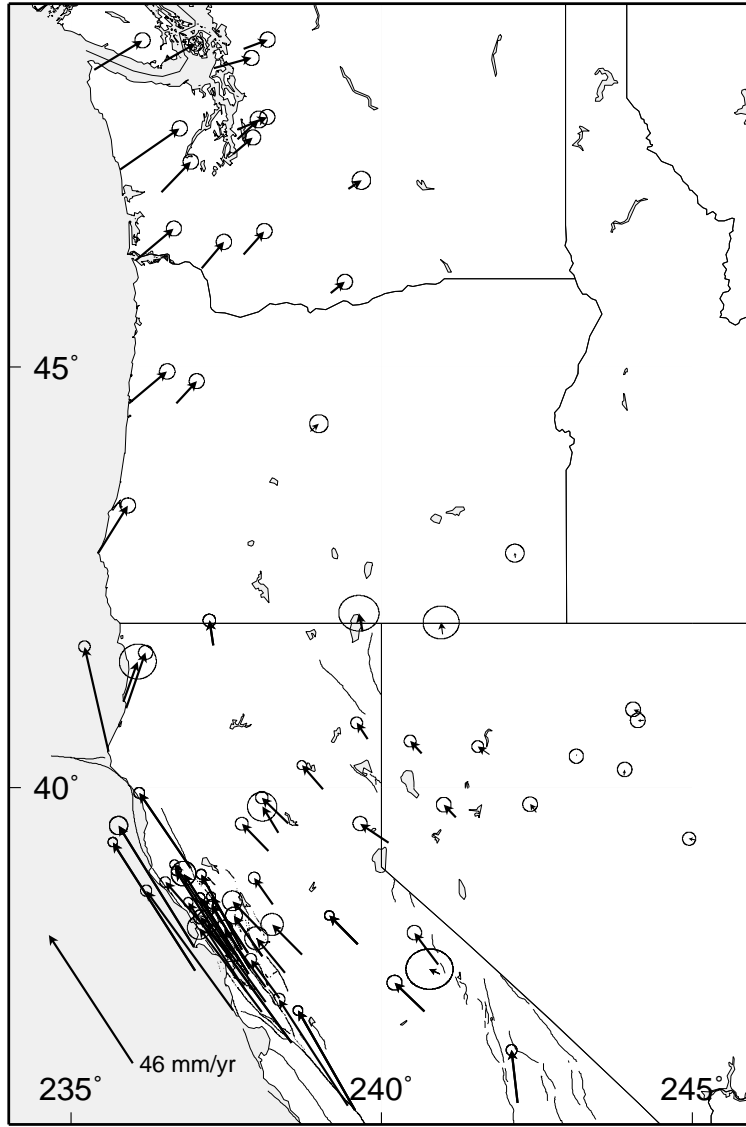
Figure 8.5: Velocities relative to stable North America for the BARD stations and other stations operated in nearby networks. Data from November 1993 to July 2000 was processed by the BSL using GAMIT software. Ellipses show 95% confidence regions, assuming white noise and $1mm/\sqrt{yr}$ random-walk noise, with the predicted Pacific–North America relative plate motion in central California shown for scale.

with tight coordinate constraints to estimate day-to-day coordinate repeatabilities, temporal variations, and site velocities.

The estimated relative baseline determinations typically have 2–4 mm WRMS scatter about a linear fit to changes in north and east components and the 10–20 mm WRMS scatter in the vertical component. Average velocities for the longest running BARD stations during 1993–2000 are shown in Figure 8.5, with 95% confidence regions. We have allowed $1mm/\sqrt{yr}$ random-walk variations in the site positions in order to more accurate characterization of the long-term stability of the site monuments and day-to-day correlations in position. The velocities are relative to stable North America, as defined by the IGS fiducial stations, which we assume have relative

motions given by *Kogan et al.,* (2000).

Most of the Sierra Nevada sites (CMBB, QUIN, and ORVB), as well as SUTB in the Central Valley, show little relative motion, indicating that the northern Sierra Nevada–Central Valley is tectonically stable. The motion of these sites relative to North America differs from the inferred motion of the western Basin and Range Province, suggesting 3 mm/yr right-lateral shear across the Walker Lane-Mt. Shasta seismicity trend. Deformation in the Pacific Northwest is generally consistent with interseismic strain accumulation along the Cascadia megathrust, the interface between the Juan de Fuca and North America plates, particularly in Washington where the velocity vectors are nearly parallel to the oblique convergence direction. Greater arc-parallel motion in Oregon and

northern California may be due to the influence of the SAF system to the south and clockwise rotation of the southern Oregon forearc (*Savage et al.,* 2000).

Deformation along the coast in central California is dominated by the active SAF system, which accommodates about 35 mm/yr of right-lateral shear. The Farallon Island site (FARB) off the coast of San Francisco is moving at nearly the rate predicted by the NUVEL-1A Pacific–North America Euler pole. Two-dimensional modeling of the observed fault-parallel strain accumulation predicts deep slip rates for the San Andreas, Hayward, and Calaveras/Concord faults are 19.3±1.8, 11.3±1.9, and 7.4±1.6 mm/yr, respectively, in good agreement with estimated geologic rates (17±4, 9±2, and 5±3 mm/yr, respectively). Most of the 46 mm/yr of relative motion is accommodated within a 100-wide zone centered on the SAF system and a broader zone in the Basin and Range Province in Nevada.

# 5.   Real-Time Processing

We are also developing real-time analysis techniques that will enable rapid determinations (∼minutes) of deformation following major earthquakes to complement seismological information and aid determinations of earthquake location, magnitude, geometry, and strong motion (*Murray et al.,* 1998c). We currently process data available within 1 hour of measurement from the 18 continuous telemetry BSL stations, and several other stations that make their data available on an hourly basis. 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. Our simulations suggest that displacements 3–5 times these levels should be reliably detected, and that the current network should be able to resolve the finite dimensions and slip magnitude of a M=7 earthquake on the Hayward fault. We are currently investigating other analysis techniques that should improve upon these results, such as using a Kalman filter that can combine the most recent data with previous data in near real-time. The August 1998 M=5.1 San Juan Bautista earthquake (*Uhrhammer et al.,* 1999) is the only event to have produced a detectable earthquake displacement signal at a BARD GPS receiver.

# 6.   Acknowledgements

# 7.   References

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# Chapter 9

# Plate Boundary Deformation Project

## 1.   Introduction

The Integrated Instrumentation Program for Broadband Observations of Plate Boundary Deformation, commonly referred to as "Mini-PBO", is a joint project of the BSL, the Department of Terrestrial Magnetism at Carnegie Institution of Washington (CIW), the IGPP at UC San Diego (UCSD), and the U.S. Geological Survey (USGS) at Menlo Park, Calif. It augments existing infrastructure in central California to form an integrated pilot system of instrumentation for the study of plate boundary deformation, with special emphasis on its relation to earthquakes. This project is partially funded through the EAR NSF/IF program with matching funds from the participating institutions and the Southern California Integrated Geodetic Network (SCIGN).

Because the time scales for plate boundary deformation range over at least 8 orders of magnitude, from seconds to decades, no single technique is adequate. We have initiated an integrated approach that makes use of three complementary and mature geodetic technologies: continuous GPS, borehole tensor strainmeters, and interferometric synthetic aperture radar (InSAR), to characterize broadband surface deformation. Also, ultrasensitive borehole seismometers monitor microearthquake activity related to subsurface deformation.

The project has three components. The first augments existing instrumentation along the Hayward and San Andreas faults in the San Francisco Bay area (Figure 9.1). During July 2001 to August 2002, five boreholes were drilled and equipped with tensor strainmeters and 3-component L22 (velocity) seismometers (Table 9.1). The strainmeters were recently developed by by CIW and use 3 sensing volumes placed in an annulus with 120 degree angular separation, which allows the 3-component horizontal strain tensor to be determined. One borehole station has also been equipped with a GPS receiver, Quanterra recording system, and downhole pore pressure sensor, and will eventually also include a tilt sensor. The other stations are in various stages of completion, primarily waiting for power and telemetry to be established. The GPS antennas at these stations are mounted at the top of the borehole casings in an experimental approach to achieve stable compact monuments. The GPS stations complement existing Bay Area stations of the BARD continuous network.

The 30-second GPS, and 100-Hz strainmeter and seismometer data is acquired on Quanterra data loggers and continuously telemetered by frame relay to the BSL. Low frequency (600 second) data (including strainmeters, for redundancy) is telemetered using the GOES system to the USGS. All data is available to the community through the Northern California Earthquake Data Center (NCEDC) in SEED format, using procedures developed by the BSL and USGS to archive similar data from 139 sites of the USGS ultra-low-frequency (UL) geophysical network, including data from strainmeters, tiltmeters, creep meters, magnetometers, and water well levels.

The second component of this project is to link the BARD network in central and northern California to the SCIGN network in southern California. The distribution of these sites allows measurement of both near-field deformation from fault slip on the San Andreas and regional strain accumulation from far-field stations. During Summer 2001, nine new continuous GPS sites were installed (see Table 8.2) in the Parkfield area spanning about 25 km on either side of the San Andreas fault. One of the receivers was contributed by the USGS and the other eight were contributed by SCIGN, while the braced monuments for all the sites were constructed using Mini-PBO funding. The new array augments the considerable geophysical instrumentation already deployed in the area and contributes to the deep borehole drilling on the San Andreas fault (SAFOD) component of Earthscope. The data are currently downloaded daily by SCIGN and archived by SOPAC. The NCEDC is currently assuming the responsibility for retrieving the data from these sites over their existing frame relay circuit at Parkfield. A subset of these sites will eventually be upgraded to real-time streaming and analyzed in instantaneous positioning mode.

The third component is InSAR, which supports skeletal operations of a 5-m X-band SAR downlink facility in San Diego to collect and archive radar data, and develop
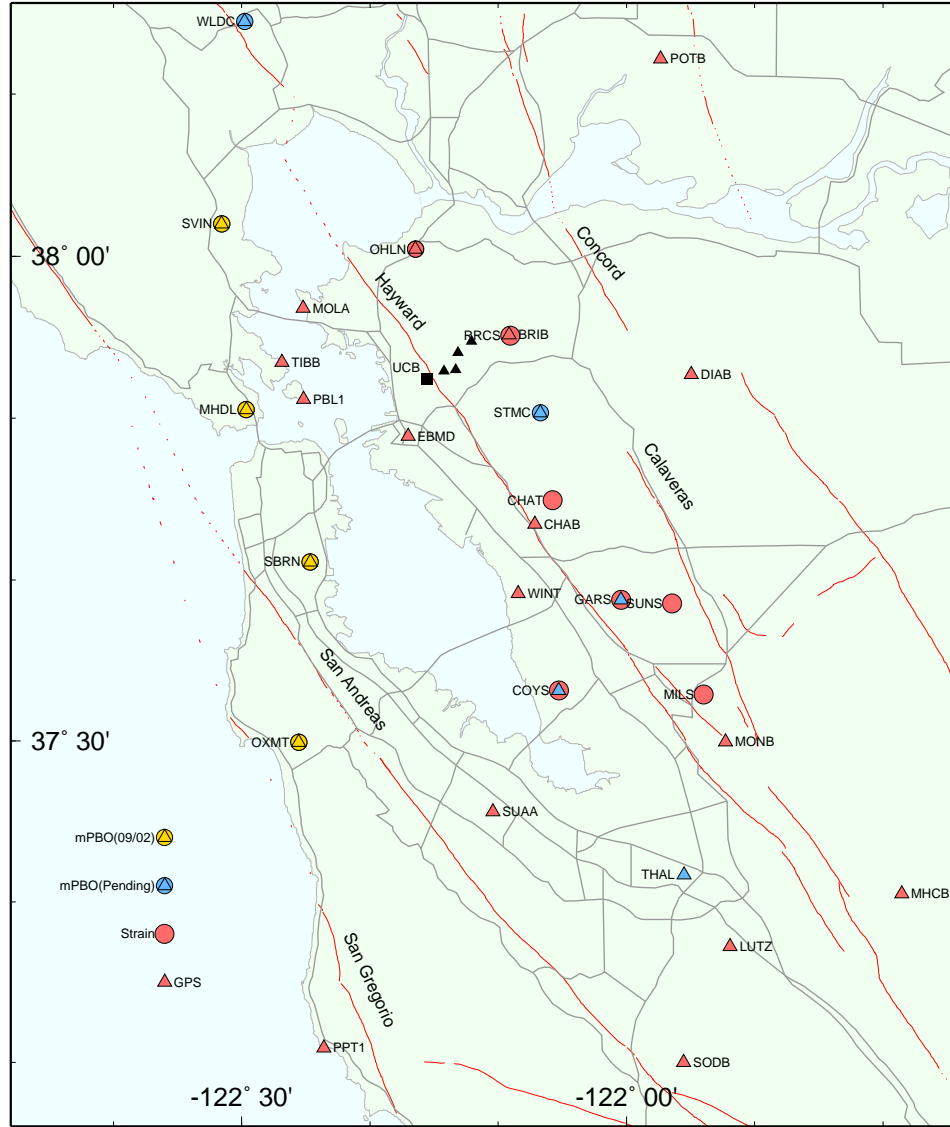
Figure 9.1: Location of existing (red), in preparation (yellow), and pending (blue) Mini-PBO sites in the San Francisco Bay area. Shown also (red) are currently operating strainmeter (circles) and BARD (triangles) stations. Blue triangles are other pending BARD stations. Black triangles are L1-system profile sites near the Hayward fault and the UC Berkeley campus.

an online SAR database for WInSAR users. The ERS-1/2 SAR data, which extend from 1992 until present, offer the only means for monitoring plate boundary deformation at high spatial resolution over all of western North America. This data set is largely unexplored mainly because data distribution is restricted by ESA and the time consuming nature of processing phase information. Our objective is to improve access to these data for plate boundary research within the strict guidelines set by ESA.

## 2.   New Site Installations

During this last year, the BSL and USGS installed the first Mini-PBO stations. Boreholes were drilled by the USGS Water Resources Division crew at five sites. The drillers used a newly purchased rig (Figure 9.2) that experienced numerous problems (hydraulics, stuck bits, etc.), which delayed the drilling considerably at several of the sites and significantly increased the costs of the project.

Figure 9.3 shows the configuration of the borehole instrument installation at the first site at Ohlone Park in Hercules (OHLN). A 6.625" steel casing was cemented into a 10.75" hole to 625'4" depth to prevent the upper,

| Code | Latitude | Longitude | Installed | Strainmeter depth (ft) | Seismometer depth (ft) | Location |
|------|----------|-----------|-----------|------------------------|------------------------|----------|
| OHLN | 38.00742 | -122.27371 | 2001/07/16 | 670.5 | 645.5 | Ohlone Park, Hercules |
| SBRN | 37.68562 | -122.41127 | 2001/08/06 | 551.5 | 530.0 | San Bruno Mtn. State Park, Brisbane |
| OXMT | 37.49795 | -122.42488 | 2002/02/06 | 662.7 | 637.3 | Ox Mtn., Half Moon Bay |
| MHDL | 37.84227 | -122.49374 | 2002/08/06 | 520.6 | 489.2 | Golden Gate Nat. Rec. Area, Sausalito |
| SVIN | 38.03325 | -122.52638 | 2002/08/29 | 527.0 | 500.0 | St. Vincent CYO School, San Rafael |
| SMCB | 37.83881 | -122.11159 | | | | St. Mary's College, Moraga |
| WDCB | 38.24088 | -122.49628 | | | | Wildcat Mt., Sears Pt. |

Table 9.1: Currently operating and planned stations of the Mini-PBO network. Strainmeter installation date is given. Depth to tensor strainmeter and 3-component seismometers in feet.

most unconsolidated materials from collapsing into the hole. Below this depth a 6" uncased hole was drilled to 676'. Coring was attempted with moderate success below 540' through poorly consolidated mudstone to about 570', and increasingly competent sandstone below. Moderately good core was obtained from 655' to 669', so this region was selected for the strainmeter installation. The section of the hole below about 645' was filled with a non-shrink grout into which the strainmeter was lowered, allowing the grout to completely fill the inner cavity of the strainmeter within the annulus formed by the sensing volumes to ensure good coupling to the surrounding rock.

The 3-component seismometer package was then lowered to 645.5', just above the strainmeter, on a 2" PVC pipe, and neat cement was used to fill the hole and PVC pipe to 565'. The pipe above this depth was left open for later installation of the pore pressure sensor in the 520-540' region. To allow water to circulate into the pipe from the surrounding rock for the pore pressure measurements, the the steel casing was perforated, a sand/gravel pack was emplaced, and a PVC screen was used at this depth. The casing was then cemented inside to 192', and outside to 16' depth. A 12" PVC conductor casing was cemented on the outside from the surface to 16' to stabilize the hole for drilling and to provide an environmental health seal for shallow groundwater flow. The annulus between the 12" conductor casing and the 6.625" steel casing was cemented from 16' to 10' depth and above was left decoupled from the upper surface to help minimize monument instability for the GPS antenna mounted on top of the steel casing.

The drilling procedures and hole instrument configuration were similar at the other four sites. At San Bruno Mt (SBRN) near Brisbane, the hole was drilled to 550' with good core through competent graywacke below 520'. Reaming of the bottom hole from the 4" core diameter to 6" was delayed considerably for retrieval of the reaming bit that broke and got lodged in the bottom of the hole. At Scarper's Ridge (OXMT) near Half Moon Bay, the hole was drilled to 712.7' depth with coring attempted

below 653' through granite. Because core was poorly recovered at the lowest depths due to inadequacies with the coring system that broke up the rock, a slightly shallower depth of 660' was chosen for the strainmeter installation.

At the Marin Headlands (MHDL) site, the drilling in October 2001 encountered hard greenstone with some fractures and clay layers between 410-608' and red and green chert below to 659'. Coring at around 545' was slow and poorly recovered. A video log of the hole showed several promising strainmeter installation regions at 500-550' depths. However, containment of high volumes of artesianing fluids from the well became increasing problematic. The hole was cased to 278', sand filled on the bottom, and cemented and plugged at the top in mid-October. In August 2002, the cement and sand were rapidly drilled out, without any artesianing problems, allowing the strainmeter and seismometer packages to be successfully installed.

At the St Vincents (SVIN) site near San Rafael, drilling in August 2002 also entailed no shortage of problems. The first hole had to be abandoned after some tungsten grinding buttons from a defective bit dislodged and could not be retrieved from the bottom of the hole. Hammer drilling through the very hard graywacke encountered throughout the hole also proved difficult due to the lack of proper stabilization on the drill string. Rotary drilling, although relatively slow, enabled penetration to 528' in the limited time available. A video log showed a promising region devoid of open fractures near the bottom of the hole where the strainmeter and seismometer packages were installed without any further difficulties.

Due to the unexpectedly high costs of drilling, only 5 boreholes could be completed under the NSF/IF grant, although additional instrumentation was purchased in anticipation of acquiring more sites. Caltrans intends to drill boreholes at several locations for the HFN project in the coming year that might be suitable for Mini-PBO installations, depending on the quality of the rock encountered at about 600' depth. Two of the already permitted potential sites, St. Mary's College (SMCB) and Wildcat Mt. (WDCB) (Figure 9.1 and Table 9.1), would

Figure 9.2: USGS Water Resources Division rig used to drill the Mini-PBO boreholes at the St. Vincents site.
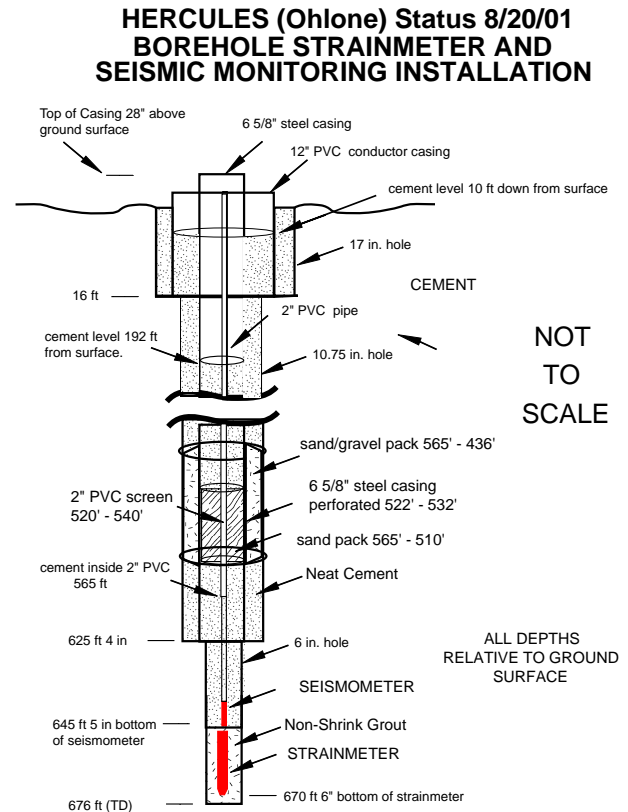


Figure 9.3: The Mini-PBO borehole configuration at Ohlone, showing the emplacement of the strainmeter and seismometer instruments downhole. The GPS receiver is mounted on the top. Figure courtesy B. Mueller (USGS).

nicely complement existing instrumentation, providing additional monitoring of the northern Hayward fault and initiating monitoring of the southern Rodgers Creek fault north of San Pablo bay.

The BSL is supervising GPS, power, frame relay telemetry, and Quanterra 4120 datalogger installation at all the Mini-PBO stations. Power, telemetry, and dataloggers are currently installed at OHLN and SBRN. The frame relay circuit at MHDL is also installed, but the power hookup has been delayed due to permitting complications that should be resolved in Fall 2002. We are currently establishing power and telemetry at the most recently installed MHDL and SVIN stations. The USGS has installed solar panels at OXMT, and soon at MHDL and SVIN, to collect the low-frequency strainmeter data prior to establishing DC power at the sites.

The BSL is developing an experimental GPS mount for the top of the borehole casings to create a stable, compact monument (Figure 9.4). The antennas, using standard SCIGN adapters and domes for protection, are attached to the top of the 6-inch metal casing, which will be mechanically isolated from the upper few meters of the ground. The casing below this level will be cemented fully to the surrounding rock. We have installed a GPS antenna at OHLN (Figure 9.5). The antenna is attached to a metal pipe symmetrically centered with respect to the casing that is welded to a cross beam and bolted inside the top of the casing, which allows access through the top of the casing to the 2" pipe for heat flow measurements. A similar mount was constructed at OXMT, but it was found to have too much play in the area where the bolts are attached to ensure long-term stability of the monument. We are currently redesigning the mount to minimize such non-tectonic motions. Preliminary analysis of 100 days of the GPS observations at OHLN shows that the short-term daily repeatabilities in the horizontal components are about 0.5-1 mm. These values are similar to those obtained with more typical monuments, such as concrete piers or braced monuments, but it is too early to assess the long-term stability of the borehole casing monument, which might also be affected by annual thermal expansion effects on the casing.
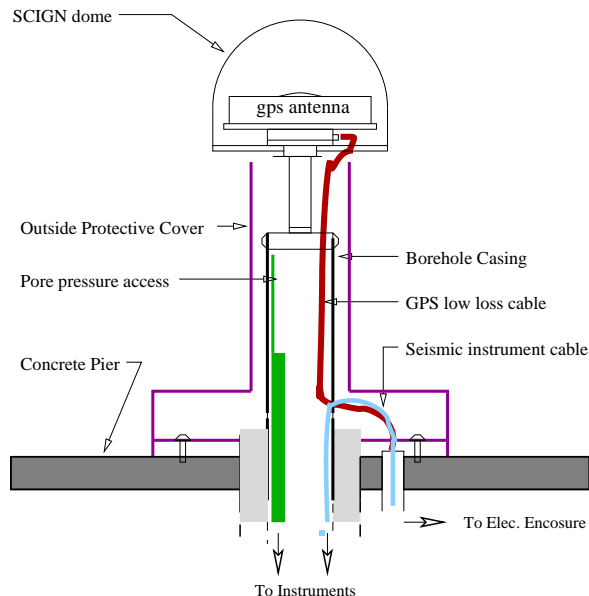
Figure 9.4: Design of the Mini-PBO GPS antenna mount on top of casing.



Figure 9.5: GPS antenna mounted on top of casing at OHLN. The final installation includes a SCIGN antenna dome and a steel protective shroud that envelopes the casing.

## 3. Strainmeter Data

We are in the initial stages of assessing the data quality of the Mini-PBO instrumentation. The newly designed tensor strainmeters appear to faithfully record strain signals over a broad frequency range. During the 9 months that the strainmeter at OHLN has been providing high-frequency data, the strain has been exponentially decaying (top, Figure 9.6). This large signal is most likely due to cement hardening effects and re-equilibration of stresses in the surrounding rock in response to the sudden appearance of the borehole. These effects can last for many years and are the principal reason that borehole strainmeters can not reliably measure strain at periods greater than a few months.

At periods around 1 day, tidally induced strains are the dominant strain signal, about 3 orders of magnitude smaller than the long-term decay signal (bottom, Figure 9.6). Since the response of the strainmeter volumes is difficult to estimate independently, theoretically predicted Earth tides are typically used to calibrate the strainmeters. Figure 9.7 shows the calibrated signals in microstrain of the OHLN strainmeter over a several day interval.

At higher frequencies, strains due to seismic events are also evident. Figure 9.8 shows a comparison of the OHLN vertical velocity seismometer and one component of the strainmeter for an M=2 event that occurred within 15 km of the station. Strains from this event are about an order of magnitude smaller than the tidal strains. We are beginning to examine the strain data for other types of transient behavior, such as episodic creep or slow earthquake displacements.

## 4. Acknowledgements

Figure 9.7: Three-component strainmeter data measured at OHLN, in microstrain. Tidal strain is used to calibrate the sensors, allowing instrument counts to be converted to microstrain. Figure courtesy M. Johnston (USGS).
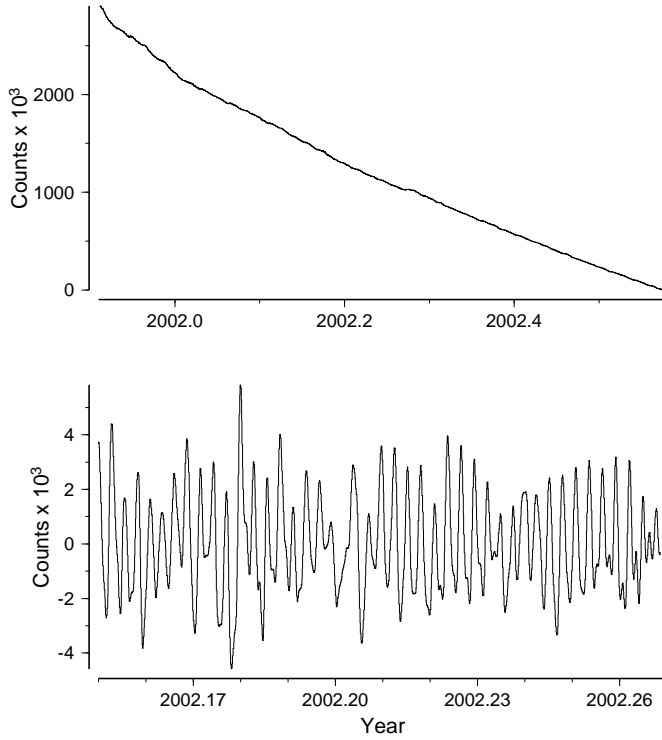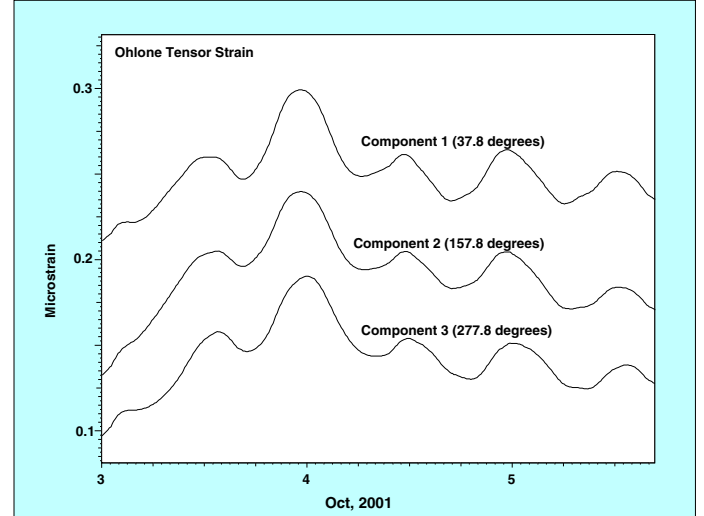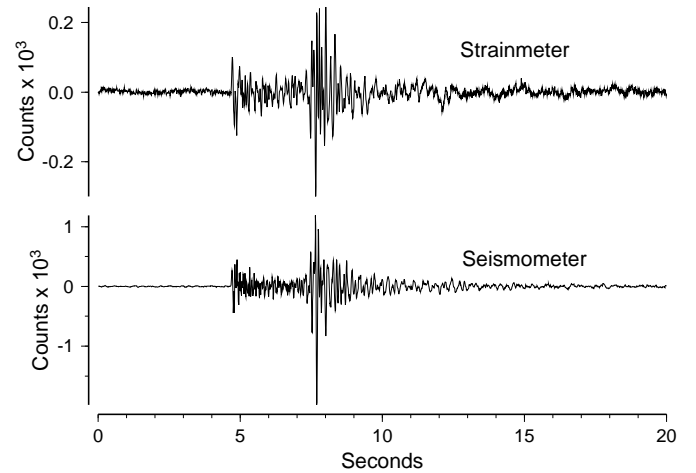
Figure 9.6: 100-second strainmeter data measured by Component 1 at OHLN, in instrumental counts. Top, 9-month timeseries with instrumental offsets due to reservoir resetting removed. Bottom, 1-month timeseries bandpass filtered at 0.5-2 day to show tidal strain signals. Note the different vertical scales.



Figure 9.8: 100-Hz strainmeter and seismometer data measured at OHLN, in instrumental counts, showing response to a M=2.3 May 2002 earthquake within 15 km of the station. Seismometer is vertical component. Strainmeter is Component 1.

# Chapter 10

# Ocean Floor Broadband Station in Monterey Bay

## 1. Introduction

This is a collaborative project between the Monterey Bay Aquarium Research Institute (MBARI) and the BSL. Supported by funds from the Packard Foundation to MBARI, NSF/OCE funds and U.C. Berkeley funds to BSL, its goal is to install and operate a permanent seafloor broadband station as a first step towards extending the on-shore broadband seismic network in northern California, to the seaside of the North-America/Pacific plate boundary, providing better azimuthal coverage for regional earthquake and structure studies.

This project follows the 1997 MOISE experiment, in which a three component broadband system was deployed for a period of 3 months, 40 km off shore in Monterey Bay, with the help of MBARI's Point Lobos ship and ROV Ventana (Figure 10.1). MOISE was a cooperative program sponsored by MBARI, UC Berkeley and the INSU, Paris, France (*Stakes et al.*, 1998; *Romanowicz et al.*, 1998; *Stutzmann et al.*, 2001). During the MOISE experiment, valuable experience was gained on the technological aspects of such deployments, which contributed to the success of the present MOBB installation.

The successful MOBB deployment took place April 9-11, 2002 and the station is currently recording data autonomously. Eventually, it will be linked to the planned (and recently funded) MARS (Monterey Accelerated Research System; http://www.mbari.org/mars/) cable and provide real-time, continuous seismic data to be merged with the rest of the northern California real-time seismic system. The data are archived at the NCEDC, as part of the Berkeley Digital Seismic Network (BDSN).

## 2. Instrumentation

The ocean-bottom MOBB station currently comprises a three-component seismometer package, a current-meter, and a recording and battery package. A differential pressure gauge (DPG) with autonomous recording (e.g. *Cox et al.*, 1984) will be deployed in the vicinity of
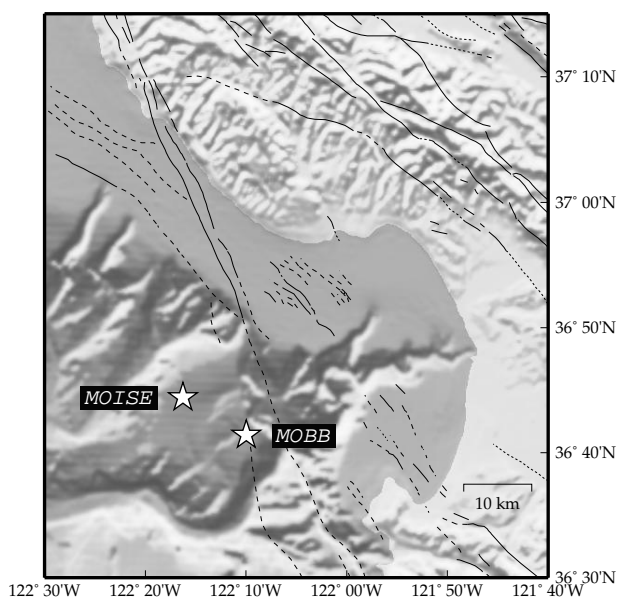


Figure 10.1: Location of the MOBB and MOIS stations in Monterey Bay, California, against safloor and land topography. Fault lines are from the California Geological Survey database. MOBB is located at 1000 m below sealevel.

the seismometer package during the next data recovery dive, in September 2002.

The seismic package contains a low-power (2.2W), three-component CMG-1T broadband seismometer system, built by Guralp, Inc., with a three-component 24-bit digitizer, a leveling system, and a precision clock. The seismometer package is mounted on a cylindrical titanium pressure vessel 54 cm in height and 41 cm in diameter, custom built by the MBARI team and outfitted for underwater connection.

Because of the extreme sensitivity of the seismometer, air movement within the pressure vessel must be minimized. In order to achieve this, after extensive testing at BSL (Chapter 11), the top of the pressure vessel was thermally isolated with two inches of insulating foam and reflective Mylar. The sides were then insulated with multiple layers of reflective Mylar space blanket, and the vessel was filled with argon gas.

The current-meter is a Falmouth Scientific 2D-ACM acoustic current meter. It is held by a small standalone fixture and measures the magnitude and direction of the currents about 1 meter above the seafloor.

The recording system is a GEOSense LP1 data logger with custom software designed to acquire and log digital data from the Guralp system and digital data from the current meter over RS-232 serial interfaces. The seismic data are sampled at 20 Hz and current-meter data at 1 Hz, and stored on a 3 GB, 2.5 in disk drive. All the electronics, including the seismometer and the current meter, are powered by a single 10kWh lithium battery.

## 3. Deployment

All installations were done using the MBARI ship Point Lobos and the ROV Ventana. Prior to the instrumentation deployment, the MBARI team manufactured and deployed a 1181 kg galvanized steel trawl-resistant bottom mount to house the recording and power systems, and installed a 53 cm diameter by 61 cm deep cylindrical PVC caisson to house the seismometer pressure vessel. The bottom mount for the recording system was placed about 11m away from the caisson to allow the future exchange of the recording and battery package without disturbing the seismometer. Prior to deployment, the seismometer package was tested extensively at BSL, then brought to MBARI where its internal clock drift was calibrated in the cold room against GPS time.

The actual deployment (04/09/02-04/11/02) occurred over 3 days. On the first dive, the seismometer package was lowered into the PVC caisson (Figure 10.2), and its connection cable brought to the site of the recording unit. On the second dive, the recording package was emplaced in its trawl-resistant mount, and connected to the seismometer package. Tiny (0.8 mm) glass beads were poured into the caisson until the seismometer was completely covered, to further isolate it from water circulation. The seismometer package is now buried at least 10 cm under the seafloor level. On the third dive, the ROV buried the cable between the seismometer and recording packages, then connected to the seismometer through the recording system, levelled and recentered the seismometer and verified that it was operational. The current-meter was also installed and connected to the recording system.

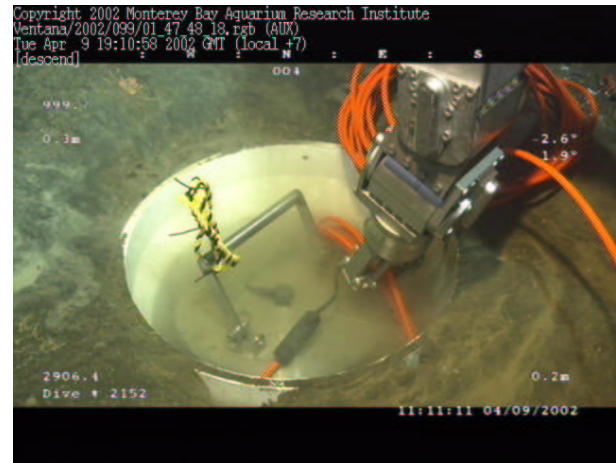On April 22nd, the ROV returned to the MOBB site to



Figure 10.2: Installation of the seismometer package inside the PVC caisson. This was later completely covered by glass beads

check the functioning of the seismometer and recording system. Some slight settling of the seismometer pressure vessel had occurred, and so the seismometer was commanded to recenter electronically. Over 3 MB of data were then downloaded from the recording system over a period of about two and a half hours, including the recordings of two regional earthquakes in California and two teleseismic events that occurred in Guerrero, Mexico and in Northern Chile.

The site was revisited two months later, on June 27th, to check the functioning of the system and replace the data recording and battery module, in the first of a series of such dives planned for the next 3 years. The following functions were performed:

1. Disconnected the current meter and seismometer from old data logger frame

2. Removed old data logger from from the trawl-resistant mount.

3. Installed new data logger frame in the trawl-resistant mount.

4. Connected the current meter to the new data logger frame.

5. Connected the ROV to the new data logger frame, and verified that the data logger was alive.

6. Connected the seismometer to the new data logger frame, and watched it reboot.

7. Centered the seismometer.

8. Turned on auto-centering on the seismometer.

9. Verified that the Guralp was seeing the GPS clock signals (NMEA time messages and pulse per second), and recorded the clock offset. During this dive, the Guralp clock was not resynchronized to GPS time.

10. Brought the old data logger frame with data logger and batteries back to the ship.

During two months of recording, many regional and teleseismic events were recorded. These data have just

started being analyzed. The plan is to revisit the site every three months to replace the data recording and battery module. Between each dive, improvements to the data acquisition software can be made. During each visit, the seismometers can be recentered, and the clock resynchronized to GPS time. Eventually, the data recording package will be plugged into the MARS cable, enabling continuous real-time data acquisition on land.

# 4. Examples of data

First, we show in Figure 10.3, the horizontal component tilt signal obtained from the seismometer mass position channels (MME, MMN). These data indicate that the seismometer package has been experiencing an exponentially decaying tilt in a south-southwesterly direction, which is also the down slope direction (e.g. Figure 10.1). The large step on day 112 (04/22/02) was caused by recentering, when the instrument was checked 12 days after installation. The small step on day 134 (05/14/02) is co-incident with the occurrence of a $M_w$ 4.96 earthquake which occurred 5 km N59W of MOBB on the San Andreas fault near the town of Gilroy. The instruments were recentered again on day 178 (06/27/02), and, with the gradual settling of the package, we expect that the subsequent tilt decay will take at least two months to reach saturation (which it did between days 161-178 on the MMN component), in time for the next planned dive and recentering operation. On the MMZ component, the semidiurnal gravitational tide is visible, riding on the tilt signal. This signal has been detrended with a 2 day running average and the scale was expanded to emphasize the fortnightly beating of the semidiurnal gravitational tides. As with the horizontal components, the largest signals are associated with rapid changes in the second derivative of the tilt, caused by recentering or by significant ground shaking (day 134).

Figures 10.4 and 10.5 show a component by component comparison of the recording of the 04/26/02 $M_w$ 7.1 teleseism in the Mariana Islands at MOBB and 3 nearby stations of the BDSN. In Figure 10.5, only the P-wave portion of the seismograms is displayed. The comparison shows consistency between the recordings of MOBB and nearby stations. On the horizontal components, there appears to be some signal-generated noise following the S waves and the Love wave, which is likely associated with ringing in the shallow mud layers. It is less apparent in the P waves in the pass-band shown, however at higher frequency the P wave shows a 3 min long coda. Such observations should be helpful in understanding the triggering of submarine landslides in strong motion events, and may be relevant for ocean floor structures such as oil platforms and pipelines. On the other hand, this type of noise may be unavoidable in a shallow buried installation. Our plan is to evaluate it further and investigate
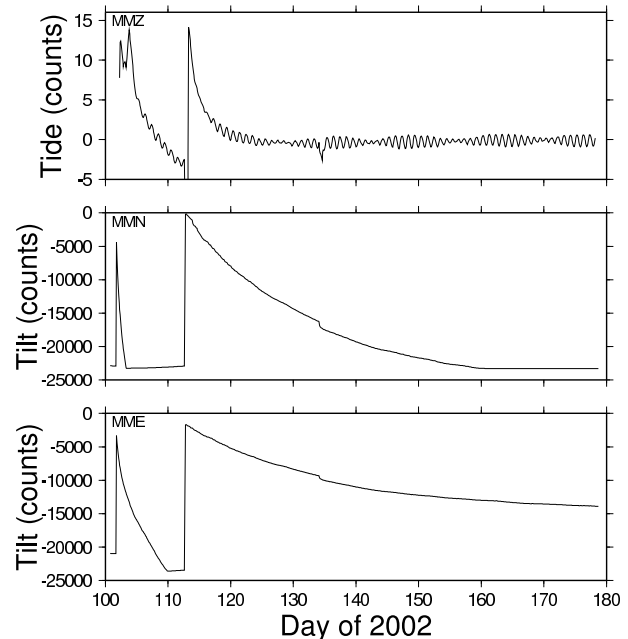


Figure 10.3: Mass position data for the time period 04/11/02-06/27/02. The large steps are associated with: 1) installation (day 100); 2) recentering (day 112), and a smaller step with a local $M_w$ 4.95 earthquake on day 134. The tide signal is clearly visible on the vertical component.

ways to suppress it by modelling and post-processing.

To further demonstrate the consistency of the MOBB data, we also show the results of a single station moment tensor inversion using only MOBB, and the comparison of the corresponding synthetic predictions with the actual data at the four other BDSN stations, for a $M_w$ 3.63 regional event which occurred on 04/23/02 on the San Andreas fault at a distance of 53.4 km from MOBB. The single station solution results in nearly identical focal mechanisms, but a slightly larger CLVD component and scalar moment, which is not unlike other single station inversions (Figure 10.6).

We plan to systematically analyze MOBB data acquired over the next year to assess the data quality and possible improvements, through post-processing and/or installation adjustments. We plan to evaluate the long term time evolution of background noise, as the system continues to settle and stabilize, and the shorter term noise fluctuations in relation to tides and currents as recorder by the current-meter (e.g. Figure 10.7) as well as the DPG (after the installation of the DPG in September 02). Since the auxiliary data are sampled at sufficiently high rates (1 sps) compared to what was available for the MOISE experiment, we will be able to investigate ways to reduce the background noise correlated with the pressure and current data at periods longer than 10 sec.
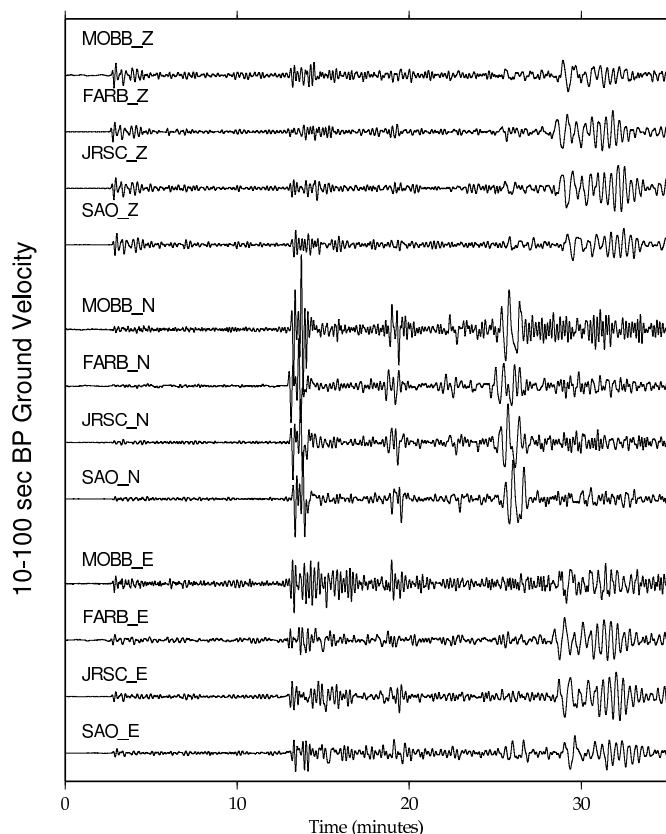
Figure 10.4: Comparison of vertical, N and E component records of the 04/26/02 $M_w$ 7.1 Mariana earthquake (depth = 85.7 km, distance = 85.2$^o$, azimuth = 283$^o$ from MOBB, at MOBB and 3 stations of the BDSN. The records have been band-pass filtered between 10-100 sec.



Figure 10.5: Same as Figure 10.4, zoomed in on the P wave portion of the seismograms

# 5.  Acknowledgements

MOBB is a collaboration between the BSL and MBARI, involving Barbara Romanowicz, Bob Uhrhammer, and Doug Neuhauser from the BSL and Debra Stakes and Paul McGill from MBARI. The MBARI team also includes Steve Etchemendy (Director of Marine Operations), Jon Erickson, John Ferreira, Tony Ramirez and Craig Dawe.

The MOBB effort at the BSL is suppored by funds from NSF/OCE and UC Berkeley.

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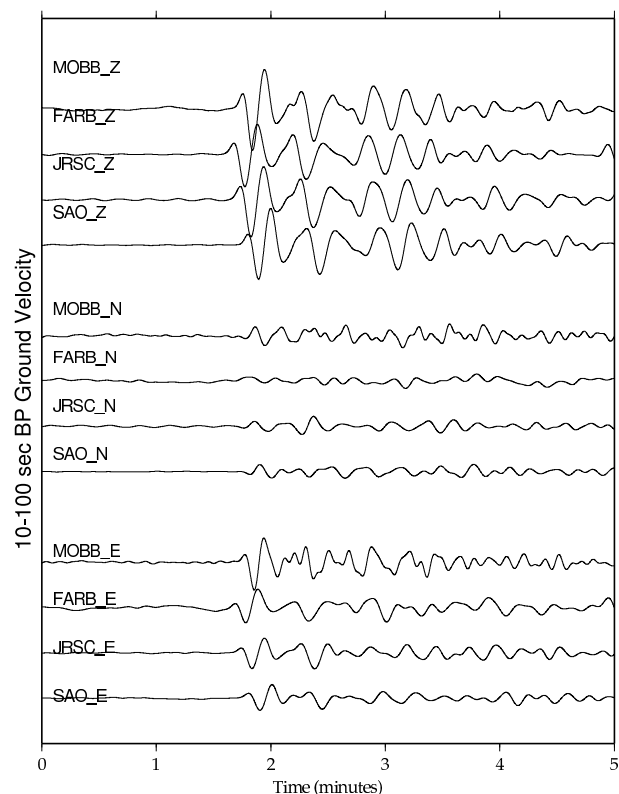
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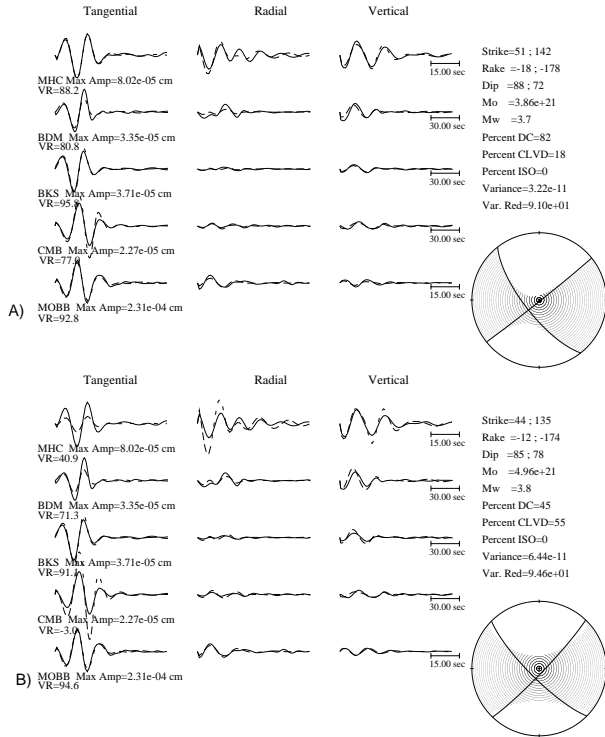
Figure 10.6: Results of moment tensor inversions for the M 3.63 regional event shown in Figure 10. Top: inversion using 4 stations of the BDSN and MOBB (BDM, BKS, and CMB are bandpassed between 0.02 and 0.05Hz; MHC and MOBB, between 0.05 and 0.10Hz). Bottom: results of inversion using only MOBB, showing the good fits of the single station solution to the other BDSN data. Courtesy of D. Dreger.
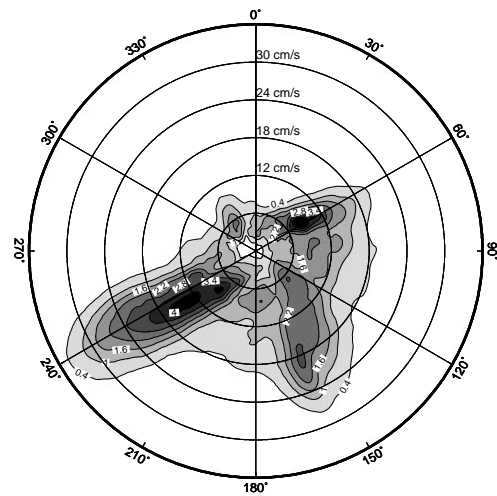


Figure 10.7: Distribution of currently available current velocity data as a function of azimuth. The contour label units are fractions of the average density distribution of the current. The two dominant maxima (centered at $60^o$ and $240^o$, i.e. orthogonal to the continental shelf) are associated with the semi-diurnal tidal currents. The third directional peak is roughly parallel to the coastline and appears to be related to the dominant ocean circulation.

# Chapter 11

# Data Acquisition and Quality Control

## 1.  Introduction

Stations from nearly all networks operated by the BSL transmit data continuously to the BSL facilities on the UC Berkeley campus for analysis and archive. In this chapter, we describe activities and facilities which cross-cut the individual networks described in Chapters 4 - 10, including the facilities in McCone Hall, procedures for data acquisition and quality control, sensor testing capabilities and proceedures, and a collaborative experiment in early warning.

While some of these activities are continuous from year to year, we have identified changes or activities which are specific to 2001-2002.

## 2.  McCone Hall Facilities

The routine data acquistion, processing, and archiving activities of the BSL are carried out in McCone Hall. The BSL facilities in McCone are designed to provide air conditioning, 100-bit switched network, and reliable power with UPS and generator.

Because of the mission-critical nature of the automated earthquake processing, most computer systems operated by the BSL run on circuits with both UPS and generator power. Air conditioning is provided through both "building air" and a separate room AC unit.

Over the years, the BSL has experienced problems with the McCone generator system, including a failure in 1999 due to a combination of a weakened power system and a leak in the water pump.

### 2.1  March 7th Power outage

On March 7, 2002, a campus-wide power outage occurred when moisture seeped into a UC Berkeley electric substation. The power failed a few minutes before 5:00 PM local time. BSL staff immediately noticed that the McCone generator failed to start (and the BKS generator as well). Phone calls were made to Physical Plant and Campus Services (PPCS), but the extended nature of the outage prevented PPCS staff from responding for over two hours.

During this time, BSL staff made several attempts to bring the McCone generator online. The initial failure of the generator was traced to a weak battery. When BSL staff replaced the battery, the generator started up and then shut itself off after several minutes, due to a leak in the water pump.

As a result of the failure of the generator, the BSL earthquake monitoring system went off the air around 5:30 PM when the UPS system shut down due to a low battery condition (the UPS is designed to carry the electrical load until the generator comes online). A subset of critical computers were brought back online when a personal generator belonging to Bob Uhrhammer was brought in around 8:00 PM. A temporary fix to the generator was provided by PPCS around 8:30 PM, which allowed the rest of the processing system to be restored. The generator was not fully repaired until March 26th, 19 days after the power outage.

The failure of the McCone generator was due to poor maintenance. Similar to the situation in 1999, it failed due to problems in the power system combined with a leak in the water pump. The BSL is working with PPCS to establish a routine of regular load tests, which should improve screening for problems such as this, as well as working with other groups to relocate the critical activities to more robust campus facilities.

The failure of the generator at Byerly Vault was traced to PPCS error. The generator had been left in a mode where it would not automatically start when power was lost. A BSL staff member went up to Byerly during the power outage and brought the generator online.

### 2.2  New facilities

The BSL is actively working with the campus to relocate the critical operations of data acquisition, processing, archiving, and distribution to a more robust facility. With assistance from the Office of the Vice Chancellor for Research, the BSL has been granted space in a building currently under construction. The building is designed to current codes and has been given special attention for post-earthquake operations. Anticipated occupancy is in FY 2004-2005.

# 3. Data acquisition

Central-site data acquisition for the BDSN/NHFN/MPBO is performed by two computer systems located at the BSL (Figure 11.1). These acquisition systems are also used for the Parkfield-Hollister electromagnetic array and for the BARD network. A third system s used primarily as data exchange system with the USNSN receives a feed from CMB, MOD, SAO, and WDC from the the NSN VSAT. This system transmits data to the USNSN from HOPS, CMB, SAO, WDC, and YBH. Data acquisition for the HRSN follows a more complicated path, as described in Chapter 6.

Data acquisition and communication with the Quanterra data loggers depends both on the software on the recording systems and at the central site.

## 3.1 MultiSHEAR

In late 1998, Quanterra provided the first release of MultiSHEAR, an enhanced version of its data acquisition software that was year 2000 compliant, and updated components of the OS/9 operating system to address the year 2000 problem. MultiSHEAR contained a number of enchancements, especially in the area of multi-site data collection, and introduced a totally new configuration procedure. The BSL worked with Quanterra during 1999 to enhance the configuration procedures to address the diverse needs of the BDSN and HFN station configurations. During November and December 1999, all of the BSL Quanterra data loggers were updated to MultiSHEAR with the corresponding OS/9 modifications, which addressed the year 2000 problems.

The two significant features of MultiSHEAR that affected the BSL were the correction of a systematic timing error of the decimated channels from SHEAR and Ultra-SHEAR software in the Quanterra data logger (previously described in the 1999-2000 and 2000-2001 Annual Reports), and the addition of multi-site data collection.

The BSL will use this multi-site data collection feature to create "hub" systems, which will acquire, store, and transmit data from several remote data loggers as well as the hub's own data. The San Francisco/Oakland Bay Bridge network will consist of two Quanterra 4120 hubs (Figure 11.2), each of which will acquire data from its own digitizers as well data from three remote diskless Quanterra Q730 systems. Each hub will provide local storage for all four sites, and will transmit the real-time the data from all four sites to the BSL over a 512Kb spread spectrum radio. The BSL developed the initial MultiSHEAR hub configuration procedure, and worked with Quanterra to refine and test the hub configurations.

## 3.2 Comserv

The BSL uses the `comserv` program for central data acquisition, which was developed by Quanterra. The `comserv` program receives data from a remote Quanterra data logger, and redistributes the data to one or more comserv client programs. The comserv clients used by REDI include `datalog`, which writes the data to disk files for archival purposes, `cdafill`, which writes the data to the shared memory region for REDI analysis, and other programs such as the seismic alarm process, the DAC480 system, and the feed for the Memento Mori Web page (Figure 11.3).

The two computers that perform data acquisition also serve as REDI processing systems. In order to facilitate REDI processing, each system maintains a shared memory region that contains the most recent 30 minutes of data for each channel used by the REDI analysis system. All REDI analysis routines first attempt to use data in the shared memory region, and will only revert to retrieving data from disk files if the requested data is unavailable in the shared memory region.

Most stations transmit data to only one or the other of the two REDI systems. The comserv client program `cs2m` receives data from a comserv and multicasts the data over a private ethernet. The program `mcast`, a modified version of Quanterra's `comserv` program, receives the multicast data from `cs2m`, and provides a comserv-like interface to local comserv clients. This allows each REDI system to have a comserv server for every station.

We have extended the multicasting approach to handle data received from other networks such as the NCSN and UNR. These data are received by Earthworm data exchange programs, and are then converted to MiniSEED and multicast in the same manner as the BSL data. We use `mserv` on both REDI computers to receive the multicast data, and handle it in an identical fashion to the BSL MiniSEED data.

# 4. Seismic Noise Analysis

BSL seismic data are routinely monitored for state-of-health. An automated analysis is computed weekly to characterize the seismic noise level recorded by each broadband seismometer. The estimation of the Power Spectral Density (PSD) of the ground motion recorded at a seismic station, provides an objective measure of background seismic noise characteristics over a wide range of frequencies. When used routinely, the PSD algorithm also provides an objective measure of seasonal and secular variation in the noise characteristics and aids in the early diagnoses of instrumental problems. A PSD estimation algorithm was developed in the early 1990's at the BSL for characterizing the background seismic noise and as a tool for quality control. As presently implemented, the algorithm sends the results via email to the engineering and some research staff members and generates a bargraph output which compares all the BDSN broadband stations by components. A summary of the

# BDSN and REDI Telemetry and Data Flow

2001/08/29

Figure 11.1: Data flow from the BDSN, NHFN, MPBO, HRSN, and BARD network into the BSL central processing facility.
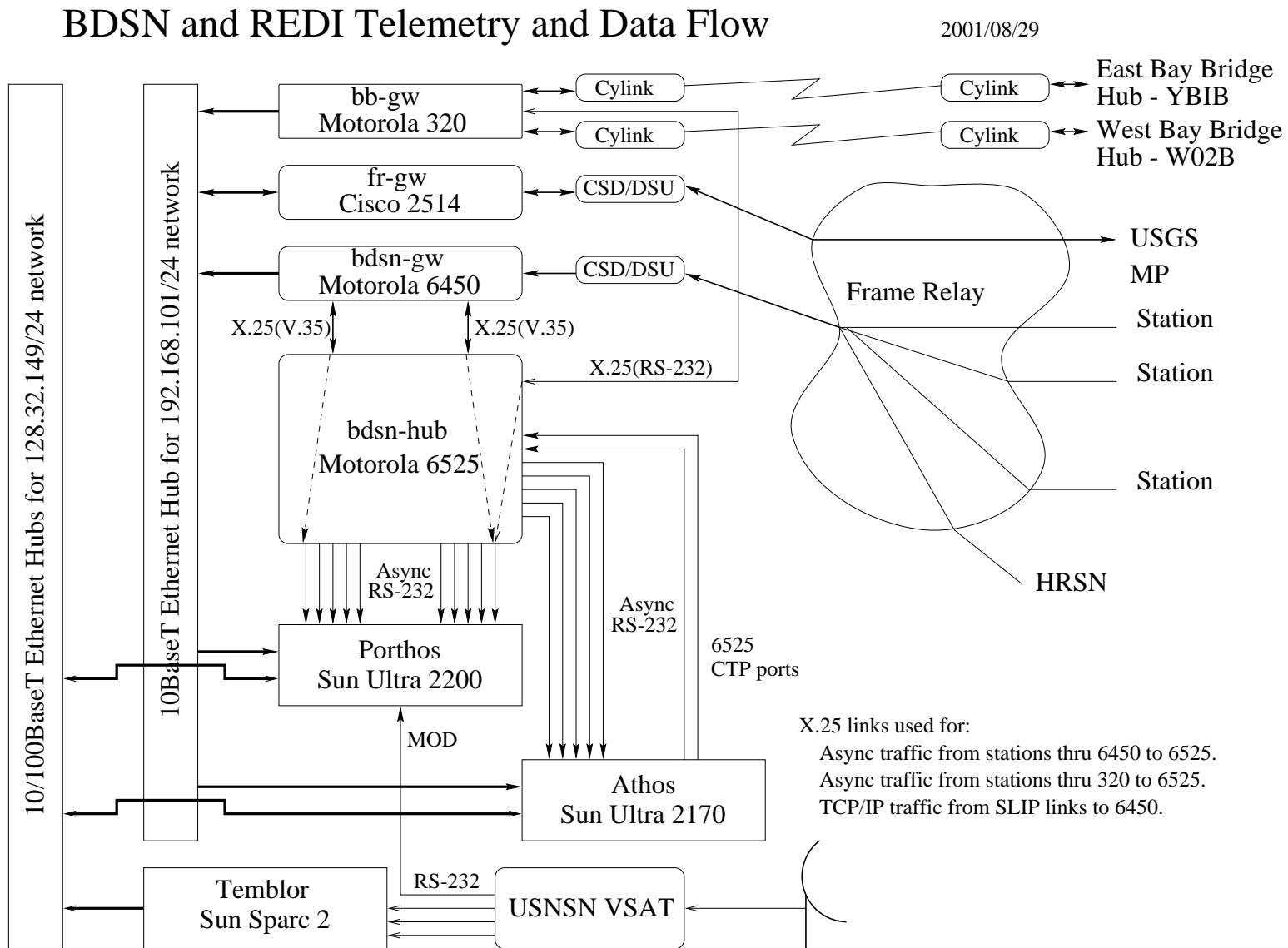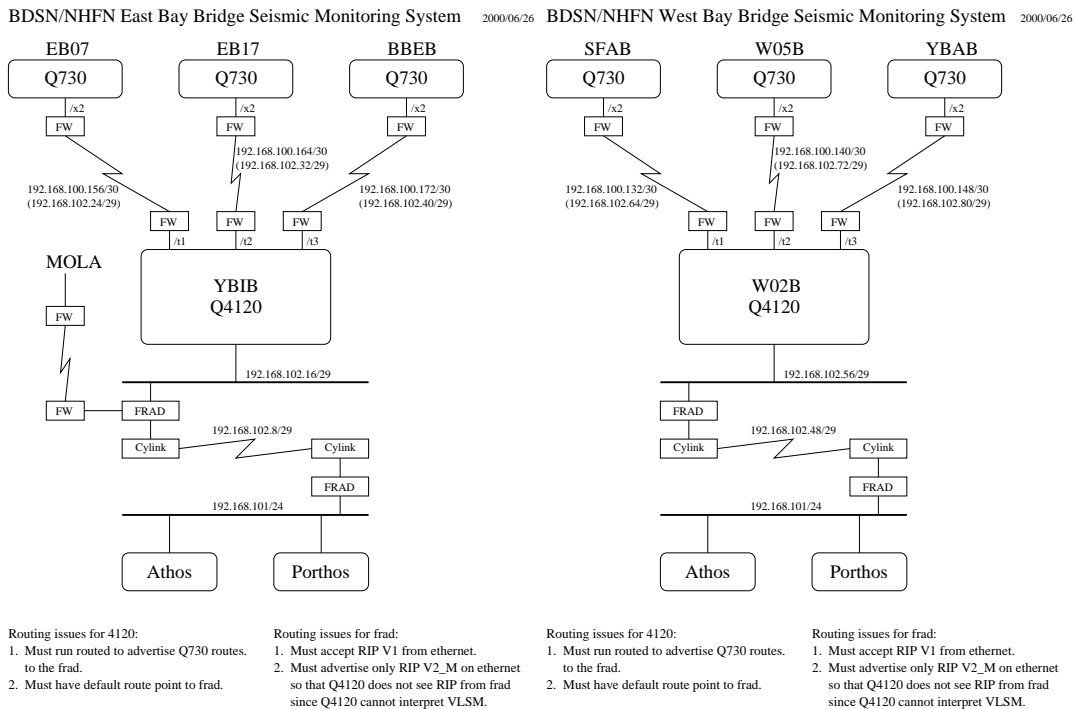
Figure 11.2: Planned data flow from the East and West Bay Bridge seismic monitoring hubs.

results for 2001-2002 is displayed in Figure 4.3.

Last year, we expanded our use of the weekly PSD results to monitor trends in the noise level at each station. In addition to the weekly bar graph, additional figures showing the analysis for the current year are produced. These cummulative PSD plots are generated for each station and show the noise level in 5 frequency bands for the broadband channels. These cummulative plots make it easier to spot certain problems, such as failure of a sensor. In addition to the station-based plots, a summary plot for each channel is produced, comparing all stations. These figures are presented as part of a noise analysis of the BDSN on the WWW at http://www.seismo.berkeley.edu/seismo/bdsn/psd/.

The PSD algorithm has been documented in previous annual reports. As reported in the past, this tool was originally written in Fortran and recently converted to C using the f2c utility in response to interest from the community. However, the resulting code was inpenetrable. As a result, a BSL undergraduate, Steve Chu, worked with Bob Uhrhammer in the spring of 2002 to write the code in C.

# 5. Sensor Testing Facility

## 5.1 Introduction

The BSL has set up an instrumentation test facility in the Byerly Seismographic Vault in order to systemati-

cally determine and to compare the characteristics of up to eight sensors at a time. The test equipment consists of an eight-channel Quanterra Q4120 high-resolution data logger and a custom interconnect panel that provides isolated power and preamplification when required to facilitate the connection and routing of signals from the sensors to the data logger with shielded signal lines. Upon acquisition of the 100 samples-per-second (sps) data from the instruments under test, PSD analysis and spectral phase coherency analysis are used to characterize and compare the performance of each sensor. Tilt tests and seismic signals with a sufficient signal level above the background seismic noise are also used to verify the absolute calibration of the sensors. A simple vertical shake table is used to access the linearity of a seismic sensor.

## 5.2 Background

BSL personnel have tested numerous sensors during the past several years and each test has been *ad hoc* in its implementation and execution. In order to expedite the setup and testing of the instruments for both BSL inhouse use and well as for other groups, such as IRIS, we dedicated an eight-channel Quanterra Q4120 data logger (see Figure 11.4) and constructed cabling and a patch panel (see Figure 11.5) to enable the simultaneous testing of up to eight sensors with high (24-bit integer) resolution sampling at 100 samples per second (for a usable bandwidth of 0-32 Hz). We housed the test equip-

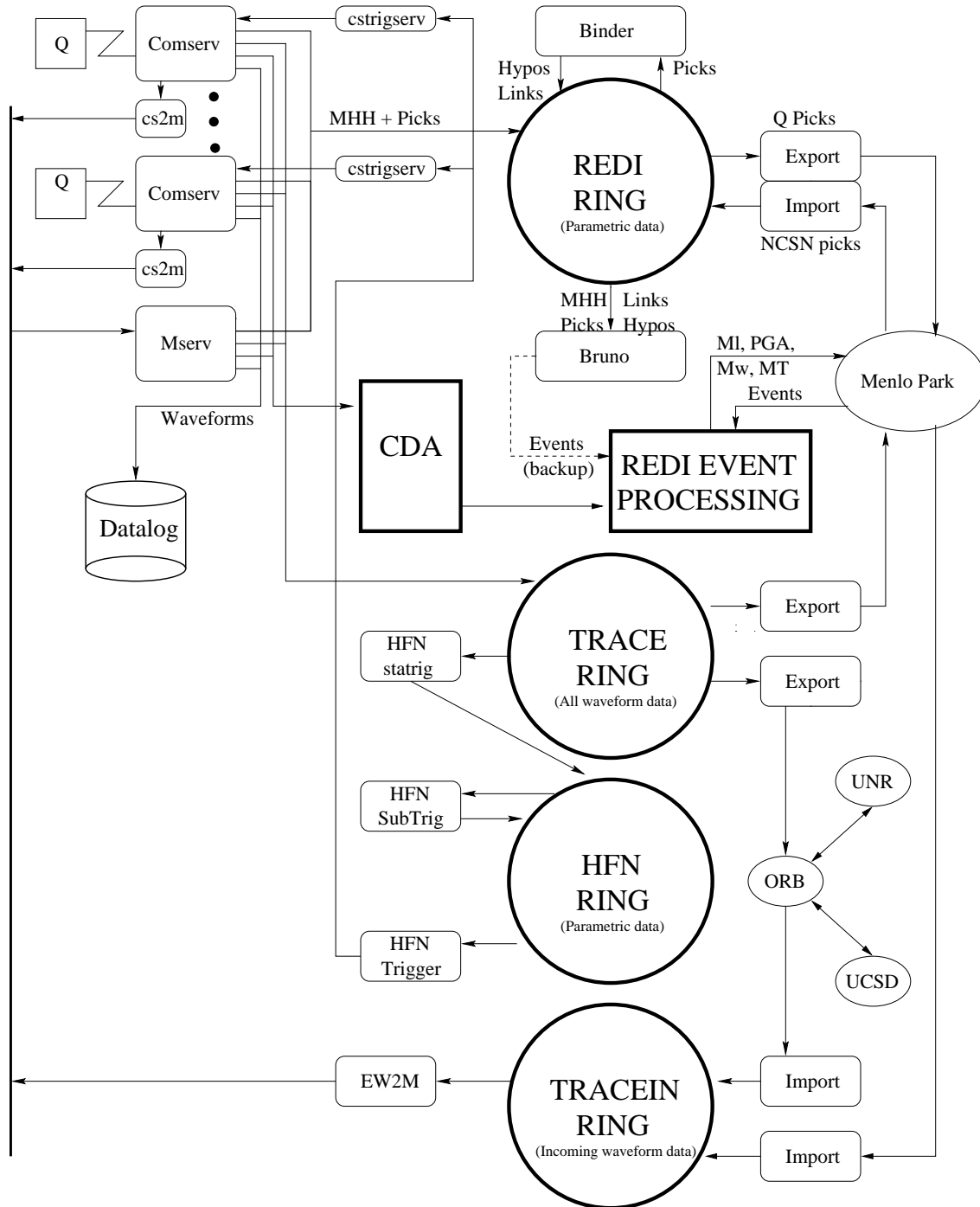# REDI Data Acquisition and Data Flow    2001/03/19



Figure 11.3: Dataflow in the REDI processing environment, showing waveform data coming in from the Quanterra data loggers (Q) into `comserv`. From comserv, data are logged to disk (via `datalog`), distributed to other computers (`mserv`), fed into the CDA for REDI processing, and spooled into a tracering for export.
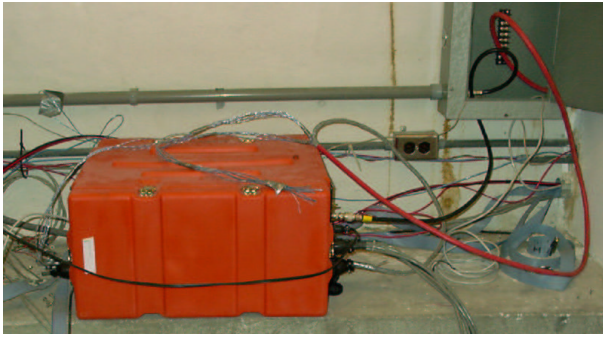
Figure 11.4: Quanterra Q4120 data logger (lower left) that records the data from the instruments undergoing testing in the Byerly Vault.

ment in the Byerly Seismographic Vault, located in an old mining drift in the Claremont shales and cherts formation in Strawberry Canyon behind the Botanical Garden. The Byerly Seismographic Vault is ideal for a test facility because it is seismically quieter than the BSL facilities on the Berkeley campus, it has all the necessary infrastructure, and because the BDSN station BKS, housed in the same vault, includes a set of Streckeisen STS-1 broadband seismometers and a Kinemetrics FBA-23 strong motion accelerometer which provide reference seismic recordings of the ground motion.



Figure 11.5: Interconnecting patch panel (top center) which routes the signals from the sensors under test (lower left and STS-2 reference sensor center right) to the Q4120 data logger.

## 5.3 Sensor Testing Methodology

Sensor testing has three aspects: 1) data acquisition; 2) sensor calibration; and, 3) sensor performance.

The acquisition of high resolution digital data is absolutely essential for the testing of modern sensors. The Quanterra Q4120 data logger, which has 24-bit integer resolution (144 dB dynamic range) with a LSB of 2.38 $\mu$V and a 40 V P-P signal handling capability, is ideally suited for this task. Data acquisition has two modes, active and passive. In the active acquisition mode, a signal is induced by appropriate means as described below. In the passive acquisition mode, the sensors signals are recorded for extended periods of time, typically from a day or so to a couple of weeks or more, to acquire samples of both the background noise level as well as various natural seismic, gravitational tide, and atmospheric signals.

The calibration methodology employed is sensor dependent. In the case of broadband seismometers, induced tilting, dynamic shaking, dynamic driving of a calibration coil, the gravitational tide signal, and comparison with ground motions inferred from known sensors are used as appropriate. In the case of strong motion accelerometers, induced tilting, dynamic shaking, and comparison with ground motions inferred from known sensors are used as appropriate. In the case of barometric pressure sensors, static elevation changes and comparison with the atmospheric pressure inferred from known sensors are used as appropriate.

Performance of a sensor is primarily characterized by determining the usable dynamic range, the linearity, and the noise characteristics. The usable dynamic range is the difference, usually expressed in dB, between the sensor saturation signal level and the sensor or background noise level. The usable dynamic range is usually frequency dependent. Characterization of the linearity and dynamic range of a broadband seismic sensor is problematic because seismic signals are a wide bandwidth transient phenomena (see the linearity and dynamic range section below). The linearity is characterized by determining the third-order intercept point. The usable dynamic range is quantified by the difference between the sensor saturation (full scale) signal level and the background signal or sensor noise floor and it is usually expressed in dB. PSD estimates of the background seismic (or sensor self noise), plotted as a function of frequency, are used to concisely quantify the performance of a broadband sensor (and also to quantify differences in the noise levels observed in various seismic vaults housing broadband seismic sensors). Another approach for characterizing the bandwidth and performance of a particular type of sensor is to simultaneously record two identical sensors placed on the same pier and calculate the phase coherency of their outputs as a function of frequency.

All of the above approaches to sensor testing have been

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employed in our analysis during the past year.



Figure 11.6: Simple vertical shake table, constructed using a Johnson-Matheson Model 6840 short-period seismometer, with a PMD sensor mounted on top of the shake table for testing.

## 5.4 Shake Table

The problem of how to shake the seismic sensors in order to test the linearity was solved by constructing a vertical component shake table from a Johnson-Matheson (J-M) Model 6840 short-period vertical seismometer as shown in Figure 11.6. The large and stiff suspension of the J-M was ideally suited for modification to a simple shake table. A platform to hold the sensor and extra springs to support the additional weight were added to the J-M seismometer so that vertical shaking could be induced by actively driving the J-M signal coil at relatively low current levels. The natural frequency of the resulting shake table was ∼1.6 Hz. We found that the
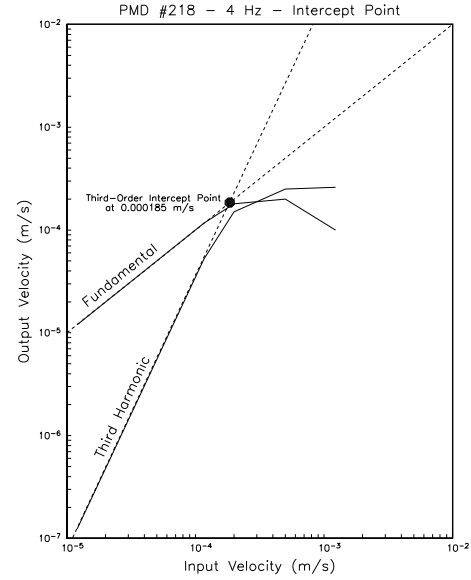


Figure 11.7: Third-order intercept point plot for PMD sensor, measured at 4 Hz.

shake table could be driven over a useful range of ∼50 dB, from ∼ $3.4x10^{-6}$m rms (limited by the background noise PSD level of ∼-136 dB at BKS) to ∼ $10^{-3}$m rms (limited by the shake table suspension travel), and over a 0.2-5 Hz frequency range by driving the signal coil sinusoidally with a WaveTek function generator. Vertical and horizontal Wilcoxon 731A accelerometers are attached to the housing of the sensor under test to directly measure the amplitude and spectral characteristics of the induced shaking for reference to output of test sensor. The table and sensor were arranged so that their center of mass was on the center line of the J-M suspension axis in order to minimize cross axis coupling.

## 5.5 Linearity and Dynamic Range

Characterization of the linearity and dynamic range of a broadband seismic sensor is problematic because seismic signals are a wide bandwidth transient phenomena while typical linearity tests utilize a narrow bandwidth continuous signal. One figure of merit that is indicative of the quality with which a seismic sensor can record the ground motion signal is Total Harmonic Distortion (THD). The THD, in percent, is defined as:

$$THD = 100 \frac{\sqrt{\sum_{k=2}^{N} a_k^2}}{a_1}$$

where: $a_1$ is the rms level of the fundamental drive signal and the $a_k$ are the rms levels of the harmonics that result from non-linear processes in the seismic sensor. Given the difficulties in reliably determining the sum

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of the $a_k$'s, we opted to measure instead the size of the third-order harmonic ($a_3$) as a function of the sinusoidal drive signal ($a_1$) and to determine the third-order intercept point. The third-order intercept point, i.e. the projected asymptotic point at which the fundamental and third harmonic signal levels are equal in amplitude, provides a useful figure of merit for the quality of a ground motion signal recorded by a seismic sensor. The methodology for determining the third-order intercept point is shown in Figure 11.7 for a PMD sensor where the fundamental and third harmonic output velocities are plotted as a function of the sinusoidal input velocity at a given frequency. Asymptotes are drawn through the fundamental and third harmonic slopes and their intersection is the third-order intercept point.

# 6.    Sensor testing in 2001-2002

## 6.1    Guralp CMG-1T Ocean Bottom Seismometer

Prior to deployment of the Guralp CMG-1TD OBS (Serial Number T1045) sensor package (Figure 11.8) on the ocean floor in Monterey Bay (MOBB - Chapter 10), we did extensive testing to verify the operation of the seismometers and the wide range leveling system (Figure 11.9), to verify the calibration of the seismometer, to determine the drift rate of the OBS clock, to characterize the background noise PSD performance of the seismometers and to calibrate the magnetometer used to determine the sensor orientation on the ocean floor.

The testing of the OBS system in the Byerly Seismographic Vault (BKS) started on 2 November with the arrival and installation of the CMG-1TD seismometer and learning the commands for unlocking, centering and checking the status of the seismometers. We determined then that the internal flux gate magnetometer was not operating properly. The test data from the CMG-1TD was telemetered to McCone Hall via a frame relay serial port. A plastic garbage can was placed over the CMG-1TD to keep dust and breezes off of the exposed sensors and electronics.

On 14 December, Cansun Guralp visited BSL to replace the flux gate magnetometer and determine the offset of the CMG-1TD internal clock.   The new magnetometer was calibrated using a Guralp-supplied turntable. The Garmin GPS receiver was connected to the CMG-1TD to check the clock offset and, based on the software reports, it appears that the CMG-1TD internal clock was 18-19 msec faster than the GPS clock. We verified the offset by connecting a 1 PPM signal (generated by external diagnostics board from Guralp's Garmin GPS receiver) into the Guralp Z digitizer, in place of the Z component seismometer and observed the same 18-19 msec difference.

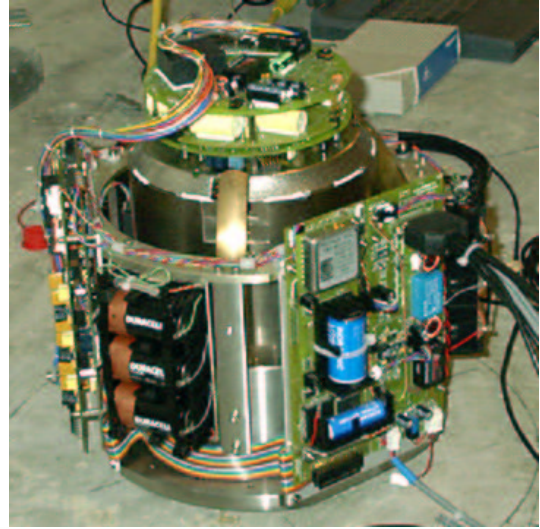During January, the CMG-1TD was operated contin-



Figure 11.8:  Photo of the Guralp CMG-1TD Serial Number T1045 seismometer in the Byerly Vault (BKS). Shown are the various circuit boards on the sides and the top of the sensor package.  Three of the nine batteries used by the leveling system are on the left front and the system clock is on the circuit board on the right. The seismometers are in the mu metal shielded container mounted on leveling gimbals in the center.
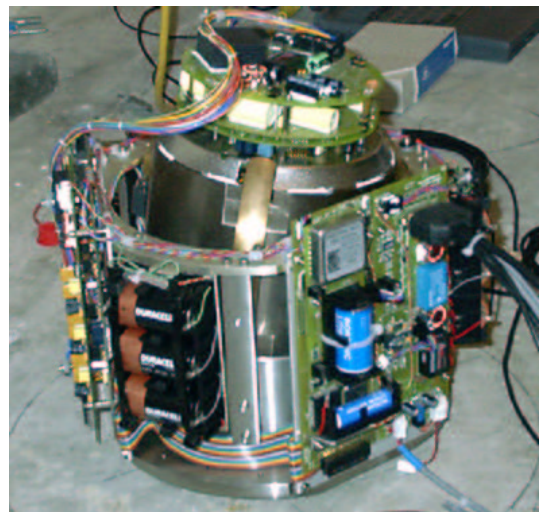


Figure 11.9: Photo taken after the seismometers were leveled with the base tilted in order to verify the operation of the wide range leveling system. Given the extreme tilt sensitivity of the CMG-1TD's 360 second pendulums, the leveling system is crucial for successful operation on the ocean floor.  Note that the central gimbal system containing the seismometers is tilted relative to the outside frame.

uously and the ground motions, inferred from the CMG-1TD and from the STS-1's operating at BKS, were compared for some large teleseisms and regional earthquakes and we verified that the transfer function of the CMG-1TD was correct. However background noise PSD analysis showed that the Z component of the CMG-1TD was very noisy at periods longer than 10 seconds, as shown in Figure 11.10. The high noise level observed on the CMG-1TD vertical component is most likely caused by air circulation around the seismometer and the noise is expected to decrease significantly when the CMG-1TD is installed in the pressure vessel. During this time it was also determined that the CMG-1TD internal clock drift rate is -236.59±1.98 microseconds/day.
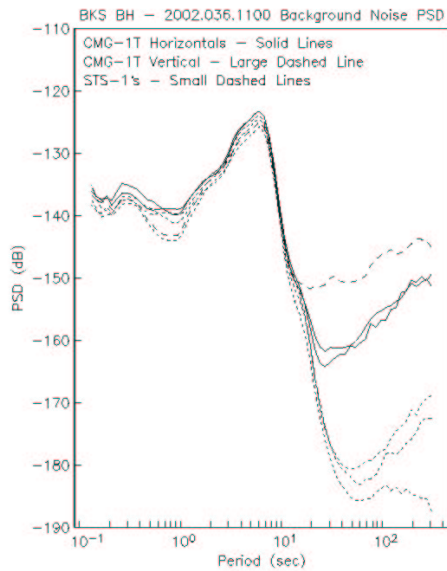


Figure 11.10: Comparison of typical background noise PSD levels observed by the CMG-1TD and the co-sited STS-1 in the BKS vault. The large dashed line and the solid lines are the Z component and horizontal component PSD's, respectively, and the small dashed lines are the STS-1 PSD's.

The CMG-1TD was installed in the titanium pressure vessel on 30 January and the pressure vessel was placed on a bed of sand as shown in Figure 11.11. Subsequent background noise PSD analysis indicated that the CMG-1TD vertical component was still very noisy at periods longer than 10 seconds. Communication with Guralp suggested several possible causes for the observed long-period noise: 1) the sand may be creaking under the weight of the pressure vessel and seismometer; 2) one or more of the calibration relays may have been left in the

cal-enable position at boot-up; 3) the air inside the pressure vessel may be convecting; or 4) something is amiss with the Z component seismometer. Tests subsequently ruled out the sand creaking and the calibration relays as the source of the problem.



Figure 11.11: Photo of the titanium pressure vessel resting on a ~1 cm thick bed of kiln dried fine sand on the concrete pier.

In a one week interval, starting on 26 February, a series of tests were done to determine their effect on the CMG-1TD background noise PSD level. The first test was to construct and install a baffle and insulating sleeve around and over the seismometer inside the pressure vessel as shown in Figure 11.12. The result was that background noise PSD at periods longer than ~10 seconds decreased by ~17 dB on the Z component. This is evidence that the air inside the pressure vessel was in fact convecting and inducing noise on the Z component. The insulation and baffle served to stratify the air and inhibit convection inside the pressure vessel. The second test was to purge the pressure vessel with dry argon gas (argon is 37% denser than air and has thermal conduction properties which tends to inhibit convection). The argon gas indeed lowered the background noise PSD level by another 6+ dB at long periods. To test the idea that the power supply may be inducing some long period noise into the system, we disconnected the power supply and powered the CMG-

1TD solely from a 12 Volt battery. The background noise PSD level subsequently decreased by another 6+dB at long periods. Finally we added insulation to the outside of the pressure vessel by draping a space blanket over the vessel and covering the vessel with a two inch thick foam box with all seams taped. The background noise PSD performance of all three CMG-1TD seismometer components are now within 5 dB of the performance of the BKS STS-1 sensors (which are more heavily insulated and installed in an nearly ideal observatory environment), as shown in Figure 11.13. The result of this testing is that CMG-1T must be appropriately insulated and the pressure vessel purged with argon gas in order to obtain the performance of which the CMG-1T is capable.



Figure 11.12: Photo of the space blanket insulation and the space filling urethane foam space filling plug in the titanium pressure vessel with the titanium end cap removed.
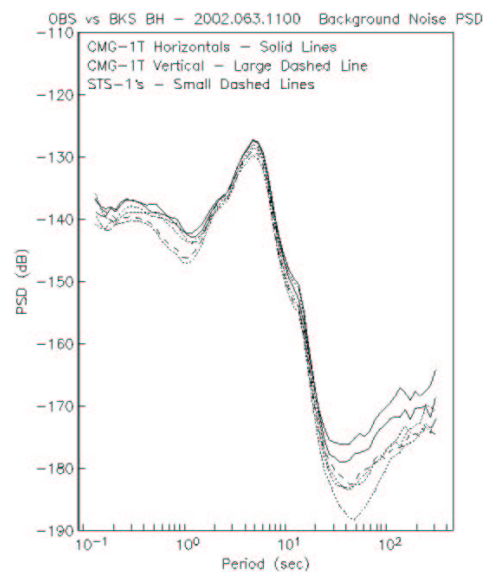


Figure 11.13: Observed background noise PSD levels for the CMG-1TD after it had been installed in the titanium pressure vessel, appropriately insulated and purged with argon gas. Note that the CMG-1TD PSD levels are within ∼5 dB of the STS-1 PSD levels at long periods.

For the final phase of the testing, the CMG-1TD and the pressure vessel were transported to MBARI on 26 March for testing in their cold room at the ∼4 degrees C temperature of the ocean floor. The cultural environment at MBARI, owing to its being situated on sand and in close proximity to the surf, makes for noisy seismic recordings with a large seven-second microseismic peak. The clock drift while operating in the cold room increased by an order of magnitude to -3191.39±2.656 microseconds/day. This was a surprise because the expectation was that the drift rate would be smaller at 4 degrees C

than at room temperature. There was insufficient time, however, to retrain the clock prior to the scheduled deployment on the ocean floor. We also did a rough check of the calibration of the flux gate magnetometer because there was some concern that the metal in the BKS Vault may have biased the original calibration results.

For details on the deployment of the MOBB system, please see Chapter 10.

## 6.2 Quanterra 680 Data Logger Noise

The question arose as to what is the typical self-noise of a Quanterra 680-family Very-Broad-Band data acquisition system (aka "Pumpkin"). The digitizer package contains identical sets of independently optically-isolated three-channel 24-bit digitizers operating at 80 Hz sampling with a least significant bit (LSB) of 2.38 microvolts and a $\pm$ 20 Volt full scale range. The self-noise was tested by operating a Q680 (s/n 921209) in the BSL lab for a couple of weeks with open inputs to the six high-resolution channels. The result, shown in Figure 11.14, is a composite based on the noise PSD observed on all six channels. The lowest self-noise occurs at 2-4 Hz frequencies and the lowest median self-noise PSD of -136.6 dB relative to 1 $V^2$/Hz occurs at 2.5 Hz. Most of the self-noise of the Q680 occurs at high frequencies (above ∼10 Hz). A -136.6 dB PSD level integrated over 1 Hz (the 2 to 3 Hz interval) is equivalent to a rms noise level of 0.067 LSB (or 0.159 microvolts) and the median value integrated over the 0-32 Hz bandwidth limited by the FIR anti-aliasing filters of the 80 Hz sampled channel is 0.601 LSB (or 1.43 microvolts). The 1.43 microvolt rms 0-32 Hz self-noise of the Q680 is approximately an order of magnitude lower than the quietest broadband sensors used by BDSN. The asymmetric variation in the inter-quartile range, given by the spacing between the medium dashed lines, is due to individual differences in the self-noise of the six high-resolution digitizer channels. There is a ∼6 dB variation in the observed self-noise PSD which is mostly due to differences in the self-noise of the individual digitizers and partly due to variations in the environmental conditions (primarily temperature variation) in the lab.

## 6.3 BDSN Instrumentation

In addition to the above testing, we tested several new broadband seismometers and strong motion accelerometers. New, and recently repaired, sensors are routinely tested before deployment in the field. We also had a few BDSN sensors, both accelerometers and broadband sensors, which either become noisy or malfunctioned during the past year and they were tested at the test facility in the Byerly Seismographic Vault to identify and characterize the problem. Most notably we have two horizontal Streckeisen STS-1 broadband seismometers which
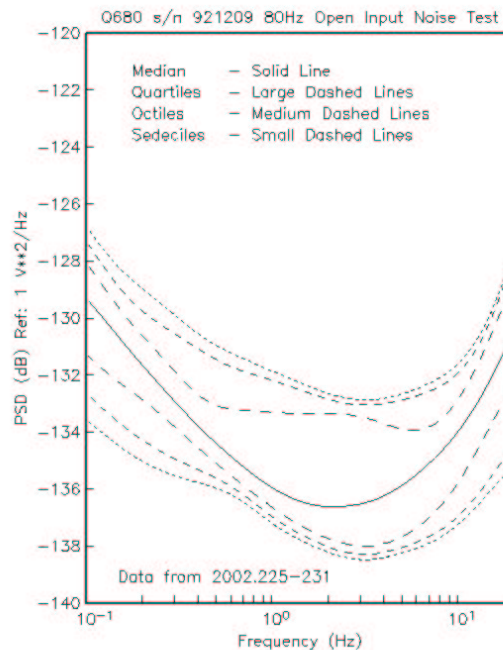


Figure 11.14: Composite open input self-noise PSD of Quanterra Q680 data logger s/n 921209. The median of the ranked PSD values is presented by the solid line, the quartiles by the large dashed lines, the octiles by the medium dashed lines, and the sedeciles (6.25 percent and 93.75 percent thresholds) are given by the small dashed lines.

became noisy over the past year and the problem was traced to rusty hinges, probably caused by operating at atmospheric pressure in a humid environment for several years. We are currently experimenting with different hinge materials for replacing the hinges.

## 7. UrEDAS Project

### 7.1 Introduction

The established joint notification system in Northern California (Chapter 12) provides accurate and reliable determination of earthquake parameters, but there is a time delay between the occurrence of an event and the determination of its size. In an emergency, this time delay prevents actions which could mitigate damage from strong ground shaking. The present configuration of the system could be improved with the capability of rapid size determination. In addition, it will be advantageous to have detection capabilities independent of the dense short-period network, especially in an emergency when

communications may be disrupted.

In an effort to develop such capability with the BDSN, we have started an experiment collocating a set of UrE-DAS (Urgent Earthquake Detection and Alarm System; see *Nakamura,* 1996), an integrated real-time earthquake warning system, at BKS. The UrEDAS detects an earthquake using only 3 sec of the P-wave recorded at a single station and has been used in Japan for over a decade to alert bullet trains to strong shaking in progress. While the weakness of UrEDAS is that it is less accurate in event parameter determination, its advantage is speed. Through this experiment we explore the development of a single-station capability of rapid earthquake detection and location/magnitude estimate using data from the BDSN stations.

## 7.2  UrEDAS Overview

UrEDAS was developed to mitigate earthquake hazards for Japanese railways, especially bullet trains that travel at a peak speed close to 200 kph. Because of the speed of the bullet trains, it is extremely important to rapidly detect hazardous earthquakes and send alarm signals to the automatic train stop system. Empirically, damage to railways occurs for events with M $>=\sim$5.5, with the damaged area generally confined within a certain distance range of the epicenters. For example, earthquakes with M6, M7 and M8 can cause damages within epicentral distances of 12, 60, and 300 km, respectively. The target area of event detection of UrEDAS is designed to be $\sim$200 km from its location along the railways. Dr. Yukata Nakamura, who was formerly at the Railway Technical Research Institute and is now the president of System and Data Research (SDR) Co., Ltd. in Tokyo, Japan, is the leader of the UrEDAS system development.

The philosophy of the UrEDAS *"front alarm"* system is to detect earthquake motions as early as possible before strong ground shaking reaches the site (*Nakamura,* 1996). The concept of such a system was originally published by Dr. J. D. Cooper in the San Francisco Daily Evening Bulletin, $3^{rd}$ November 1868. At the time Cooper addressed the importance of an automated early warning system alarm as well as the likely problems of false alarms and the necessity of public education for the warning. However, the technical expertise at the time was inadequate for construction such an alarm system. In 1972 the Earthquake Research Institute of the University of Tokyo proposed the development of an automated system similar to that suggested by Cooper. The Japanese National Railways (JNR) was interested in this concept and they promoted the system development. The JNR completed the development of a Coast-line Detection System for the Tohoku Bullet Train Line in 1982 (*Nakamura and Saito,* 1982), and it was the prototype that has the same basic function of the present UrEDAS system.

UrEDAS utilizes a single system that consists of two sets of three-component seismometers, a set of velocity sensors with $T_o$=1 sec (short-period sensors with moving coil designed for events up to M$\sim$6) and a set of force feedback velocity sensors with a 0.1-10 Hz frequency passband (long-period sensors designed for larger events), for stable determination of small to large events. The system uses a velocity threshold to detect events and the epicentral azimuth is estimated from the direction of the initial motion projected on the horizontal plane. An estimate of the distance and magnitude is based on frequency content and amplitudes of the first three seconds of the P-wave motion. If the S-wave is detected, the estimates of distance and magnitude are revised. The epicentral distance ($R$) is estimated using the relation $logR = a \cdot logA + b \cdot logT + c$ where $A$ is the amplitude of the initial P-wave motion (in mkine), $T$ its prominent period, and $a, b,$ and $c$ are constant. The magnitude is estimated from the prominent period ($T$) of the initial P-wave motion using the relation $M = 3.2 \cdot logT + 5.26$.

An alarm can be issued if hazardous earthquake is detected from the P-wave motions. However, it is not always easy to detect an event from the P-wave alone and there is a trade-off between the detection threshold and the rate of false alarms. The primary advantage of UrEDAS is that the system can provide event information in $\sim$3 seconds following the detection of a P-wave at a single site. The quality of the parameter determination depends on the conditioning and tuning of the system for site specific effects and thus the pre-conditioning is important in the determination procedure. Also, the magnitude estimation using just the first three seconds of the P-wave motions may not always be reliable. It is also possible that the station location happens to be near a P-wave node of the focal mechanism. To overcome the weakness of the single system algorithm, each of the UrEDAS stations distributed along the railways is linked to a centralized system to provide better estimates of the event parameters.

## 7.3  UrEDAS Installation at BKS

Since 1984, JNR has tested the UrEDAS system in various areas where high-quality location and magnitude determinations are available from dense regional short-period networks. In November 1999 the crew of SDR visited BSL to discuss a possible joint experiment with UrEDAS. The seismologists at BSL agreed to test the UrEDAS performance by collocating it at one of the BDSN stations. We chose the Byerly Vault (station BKS) for its low noise level and accessibility and because it includes a set of Streckeisen STS-1 seismometers and a Kinemetrics FBA-23 strong motion accelerometer and because the station has been operational since June 1962 and the site specific characteristics of the seismic wave propagation are fairly well known.

The initial system installation was completed with the

event detection and notification in February 2001 and was upgraded to transmit waveform data to the BSL in July 2001. The SDR crew visited the site in July 2002 to check on the equipment and to revise the values of the parameters used by the UrEDAS algorithms. Figure 11.15 shows the UrEDAS sensors and Figure 11.16 shows an illustration of the UrEDAS network configuration.
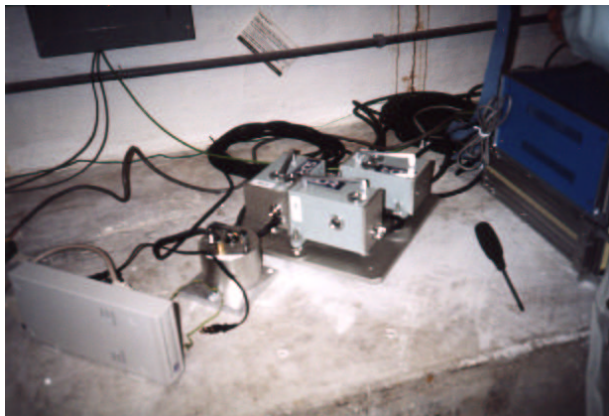


Figure 11.15: UrEDAS sensors installed at BKS site. The dedicated PC-based processing system (not shown here) is located in an adjacent room.

## 7.4 Discussion

Since February 2001, there have been 283 UrEDAS detected events, and 151 of these correspond to events in the NCSN earthquake catalog (within a 500 km radius and with a theoretical P-wave onset time at BKS within 20 seconds of the UrEDAS detection time). The 132 uncorrelated UrEDAS events are presumably a mix of teleseisms (which UrEDAS has a tendency to mislocate as local events), some small local events near Berkeley (which are below the NCSN magnitude threshold), and a few random noise triggers.

To date UrEDAS readily detects the occurrence of local/regional events from the P-wave signal as shown in Figure 11.17. It also does a fair job of determining the source distance out to 160 km or so (see Figure 11.18) but the azimuth determination is basically unusable as shown in Figure 11.19. UrEDAS also has biased magnitude estimates as shown in Figure 11.20. The UrEDAS algorithm assumes a one-dimensional velocity model with straight line propagation paths and a three-dimensional model of the crustal structure will likely be required to significantly improve the azimuthal estimates. Also, the magnitude estimation algorithm needs further tuning.

Assuming that the primary goal is to determine the event location and size as rapidly as possible, the fastest approach will prove to be a hybrid approach where the remote stations determine the azimuth and ramp growth
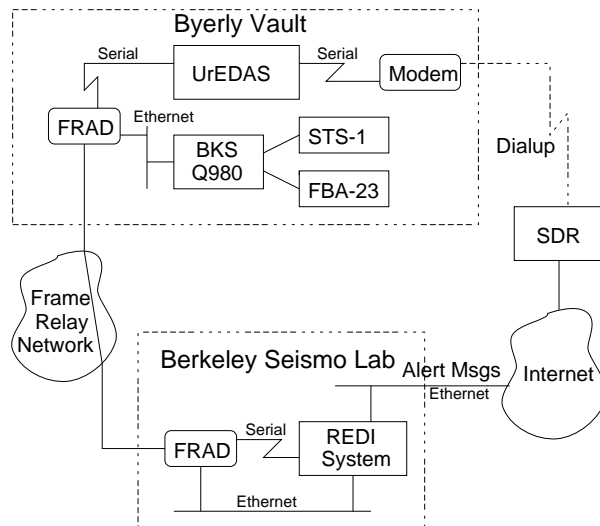


Figure 11.16: Schematical illustration of the UrEDAS collocation experiment with a Streckeisen STS-1 broadband instrument and a Kinemetrics FBA-23 strong motion accelerometer with a Quantera Q980 data logger at BKS.

rate and associated uncertainties and the central site uses a fuzzy logic algorithm to determine the location and size of the event. The primary advantage of this hybrid method is that the ramp growth rate can be reliably determined before the S-wave arrives. In the limiting case, and with a sufficiently high station density, one could even go so far as to determine and report from the remote sites using only the broadband P-wave impulse, and associated azimuth and apparent angle of incidence and estimates of their resolution and have the central site coalesce the data into a viable and rapid event report.

The critical issue for a successful installation of a UrEDAS type system in the BDSN is the calibration of specific site effects at individual stations. A joint use of the single station detection system with the current northern California earthquake notification system would significantly increase the capability of real-time earthquake warning system.

The current UrEDAS system uses a dedicated PC and the SDR personnel have indicated that a UrEDAS/UNIX version of the algorithm is available. The UNIX version generates the same message format as does the PC-based system. The advantage of the UNIX based system is that, besides running on the BSL computers, it can process data from any seismometer or seismometer/filter system that can output ground acceleration in the 0.1-10 Hz passband at 100 sps. The UNIX version of the UrEDAS algorithm is hard wired for 100 sps acceleration data provided in Gals (to four decimal places) so we would need to generate a structure which supplies the algorithm with
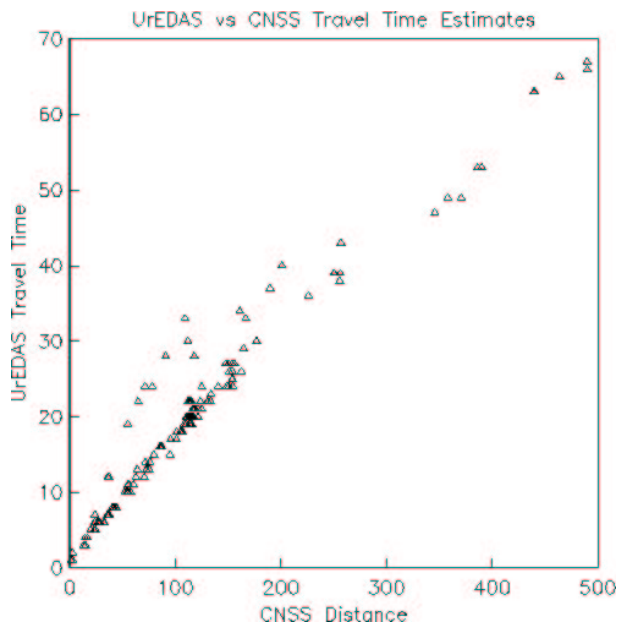
Figure 11.17: UrEDAS inferred travel time (detection time minus origin time) versus CNSS epicentral distance to BKS. The UrEDAS detection time mostly correspond to the P-wave arrival time for a majority of the detected events at distance less than ~160 km. At larger distances there is increased scatter and fewer events detected.



Figure 11.18: UrEDAS reported distance versus CNSS epicentral distance to BKS. The correlation is best at distances of less than ~160 km and poor at larger distances.

a date/time stamp amd the three acceleration components (Z,N,E) in Gals and a rate of 100 per second with a specific comma delimited format: "20020607114810.00, +24.4356, -21.5642, +14.9547" (for example). The primary disadvantage of the UrEDAS/UNIX processing is that it will lag several seconds behind real-time (~5-10, say), due to the packet transmission protocol that we use to transmit the data to BSL. The UrEDAS/UNIX source code is proprietary property of SDR and will not be made available to BSL.

# 8.   Acknowledgements

# 9.   References

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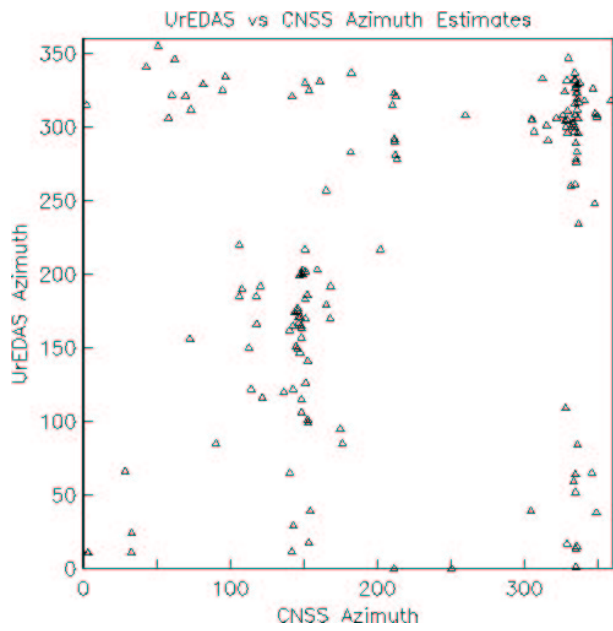
Figure 11.19: UrEDAS reported azimuth versus CNSS epicentral azimuth from BKS. The UrEDAS azimuth estimate is highly biased by the local lateral structure across the Hayward Fault zone. The azimuth estimates tend to cluster around ∼150 and ∼340 degrees owing to refraction of the P-wave along the SW (fast) side of the fault zone.

*tute, 37,* 112-127,1996.

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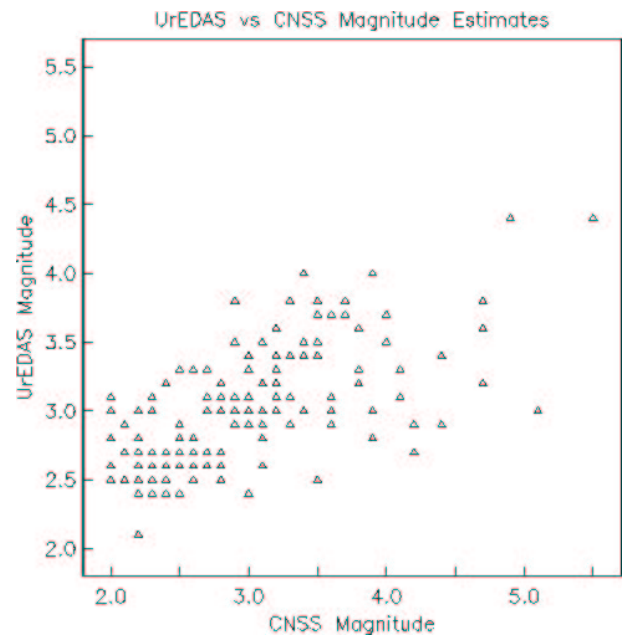
Figure 11.20: UrEDAS reported magnitude versus CNSS reported magnitude. The UrEDAS magnitude estimate is biased high for small events M<∼3 and low for larger events.

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# Chapter 12

# Northern California Earthquake Monitoring

## 1. Introduction

Analysis of the data produced by BSL networks begins as the waveforms are acquired by computers at UC Berkeley, and ranges from automatic processing for earthquake response to analyst review for earthquake catalogs and quality control.

Over the last 9 years, the BSL has invested in the development of the hardware and software necessary for an automated earthquake notification system (*Gee et al.,* 2002; *Gee et al.*, 1996). The Rapid Earthquake Data Integration (REDI) project is a research program at the BSL for the rapid determination of earthquake parameters with three major objectives: to provide near real-time locations and magnitudes of northern and central California earthquakes; to provide estimates of the rupture characteristics and the distribution of ground shaking following significant earthquakes, and to develop better tools for the rapid assessment of damage and estimation of loss. A long-term goal of the project is the development of a system to warn of imminent ground shaking in the seconds after an earthquake has initiated but before strong motions begin at sites that may be damaged.

In 1996, the BSL and USGS began collaboration on a joint notification system for northern and central California earthquakes. The current system merges the programs in Menlo Park and Berkeley into a single earthquake notification system, combining data from the NCSN and the BDSN.

This year, significant progress was made in the development of the California Integrated Seismic Network.

## 2. Joint Notification System Overview

Figure 12.1 illustrates the distributed nature of the current joint notification system in northern California.

On the USGS side, incoming analog data from the NCSN are digitized, picked, and associated as part of the Earthworm system (*Johnson et al.*, 1995). Preliminary locations, based primarily on phase picks from the NCSN, are available within seconds, while final locations and preliminary coda magnitudes are available within 2-4 minutes. Earthworm reports events - both the "quicklook" 25 station hypocenters (without magnitudes) and the final (unreviewed) solutions (with coda magnitudes) to the Earlybird alarm module in Menlo Park. This system sends the Hypoinverse archive file to the BSL for additional processing, generates pages to USGS and UC Berkeley personnel, and distributes information via the Quake Data Distribution System (QDDS).

Once an event is declared, additional Earthworm processing at the USGS generates ground motion amplitudes from NCSN and NSMP stations and loads them into a database. A process known as ShakeMapFeeder extracts amplitudes from the database and pushes them to the ShakeMap system (*Wald et al.*, 1999) implemented in Menlo Park.

On the UC Berkeley side, the Hypoinverse archive file is normally used to drive the REDI processing system. The REDI processing is divided into two systems - routine or "standard" processing (local magnitude, ground motion amplitudes, and moment tensors) - and the finite-fault processing added last year (Figure 12.2). Each REDI system provides several "stages" of processing, and the attributes of events such as magnitude, the "age" (time since origin), and number of associated phases are used to determine the appropriate processing. The REDI stage structure allows processing to be scheduled (for example, wait 5 minutes after the origin time before scheduling a moment tensor computation) as well as prioritized (for example, process the magnitude 6 before the magnitude 2).

In "abnormal" situations, such as when communication links between the BSL and the USGS are disrupted, the BSL can drive the REDI system using events detected based on BDSN data alone. The BSL has implemented the same association algorithm used in the Earthworm system in Menlo Park, using Murdock-Hutt phase detec-

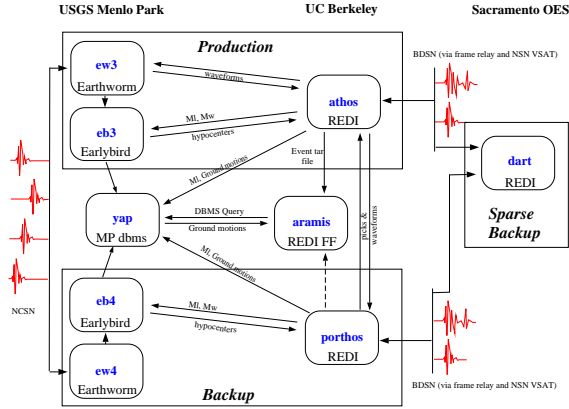**Northern California Earthquake Notification System**
Current Implementation

Figure 12.1: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley. This figure also illustrates the newly added finite-fault and ShakeMap capability, which is handled on a separate system, as well as the independent processing system in Sacramento.

tions and/or picks from an Earthworm picker.

## 2.1 Standard Processing

Stage 0 of the "standard" processing provides initial event handling. It can accept either Hypoinverse files from the USGS (the normal source of event information) or events generated from the local associator. If the preliminary magnitude estimate is less than 3.0, no additional processing is performed and event information is distributed if appropriate.

Stage 1 is initiated for all events with preliminary magnitudes greater than 3.0 and for events with no preliminary magnitude. In this stage, broadband waveforms are processed to produce Wood-Anderson synthetics and estimates of local magnitude are generated. This stage uses the preliminary magnitude and a distance criterion to decide which channels to analyze.

Stage 2 generates ground-motion amplitudes for use in ShakeMap and other applications. Stage 2 currently generates estimates of peak ground acceleration, peak ground velocity, and peak ground displacement from BDSN acceleration records, but does not produce estimates of spectral acceleration.

Stage 3 performs the automated moment tensor analysis. In this stage of REDI processing, both the waveform modeling method of *Dreger and Romanowicz* (1994) and the surface wave inversion technique of *Romanowicz et al.* (1993) are run for every qualifying event (earthquakes with $M_L$ greater than 3.5). Each algorithm produces an estimate of the seismic moment, the moment tensor solu-

tion, the centroid depth, and solution quality. The REDI system uses the individual solution qualities to compute a weighted average of moment magnitude, to compare the mechanisms using normalized root-mean-square of the moment tensor elements (*Pasyanos et al.,* 1996), and to determine a "total" mechanism quality.

In 2000-2001, two new stages were added to standard REDI processing. Stage 4 extracts the waveform data required for the finite-fault processing and Stage 5 "packs" the event up and ships it to the REDI finite-fault system running on aramis.

## 2.2 Finite-Fault Processing

During 2000-2001, the estimation of finite-fault parameters was migrated from the development platform to the REDI operational environment, new modules were developed to use the finite-fault parameters to simulate near-fault strong ground motions, and the results integrated into the generation of ShakeMap (*Dreger and Kaverina*, 2000; *Dreger and Kaverina*, 1999).

In Stage 0, waveform data are prepared for inversion and rough estimates of the fault dimensions are derived using the empirical scaling relationships of *Wells and Coppersmith* (1994). Using these parameters to constrain the overall dimensions of the extended source, the stage tests the two possible fault planes obtained from the moment tensor inversion over a range of rupture velocities by performing a series of inversions using a line-source representation. In addition to the identification of the fault plane and apparent rupture velocity, this stage yields preliminary estimates of the rupture length, dislocation rise time, and the distribution of slip in one dimension.

Stage 1 combines the results of the line-source inversion with the directivity-corrected attenuation relationships of *Somerville et al.* (1997) to simulate ground motions in the near-source region. "FFShake" computes peak ground acceleration, peak ground velocity, and spectral response at 0.3, 1.0, and 3.0 sec period, which are the values used in ShakeMap, for a grid of pseudo-stations in the vicinity of the epicenter. The predicted ground motions are automatically incorporated in ShakeMap updates as described below.

In Stage 2, the second component of the finite-fault parameterization uses the best-fitting fault plane and rupture velocity from Stage 0 to obtain a more refined image of the fault slip through a full two-dimensional inversion. If line-source inversion fails to identify the probable fault (due to insufficient separation in variance reduction), the full inversion is computed for both fault planes. In the present implementation, the full inversion requires 20-30 minutes per plane, depending on the resolution, on a Sun UltraSPARC1/200e.

Stage 3 completes the cycle by simulating the near-fault strong ground motion parameters by convolving the velocity structure response with the finite-fault slip dis-

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**"Standard" REDI Processing**

REDI Event Scheduler/Notifier — Multi-Stage Event Processing Queue

| Stage 0 | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|---|---|---|---|---|---|
| All selected events | $M \geq 3.0$ | $M \geq 3.5$ | $M \geq 3.5$ | $M \geq 5.5$ | $M \geq 5.5$ |
| Location String Relocation (BDSN) | Revised Magnitude Ml | Peak Ground Motions Duration of Shaking (Spectral Accel *) | Moment Tensor Moment Mag Mw | Extract waveform data for Finite Fault | Package event for Finite Fault |

1. Pager, Email, (QDDS)

1. Pager, Email, (QDDS)
2. Ml to EBird
3. Ml file to MP/DBMS
4. Event.txt to ShakeMap

1. Pager, Email
2. GM file to MP
3. Event.txt to ShakeMap

1. Pager, Email, (QDDS)
2. Event.txt to ShakeMap
3. Mw file to MP/DBMS, (EBird)

1. Tar file to FF machine.

(Event tar file)

**Finite-Fault REDI Processing**

REDI Event Scheduler/Notifier — Multi-Stage Event Processing Queue

| Stage 0 | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| $M \geq 5.5$ | $M \geq 5.5$ | $M \geq 5.5$ | $M \geq 5.5$ |
| Finite Fault Line Source | FFShake | Finite Fault 2d model | FFShake |

1. (Pager, Email)

1. (Pager, Email)
2. Estimates.xml & Event.txt to ShakeMap

1. (Pager, Email)

1. (Pager, Email)
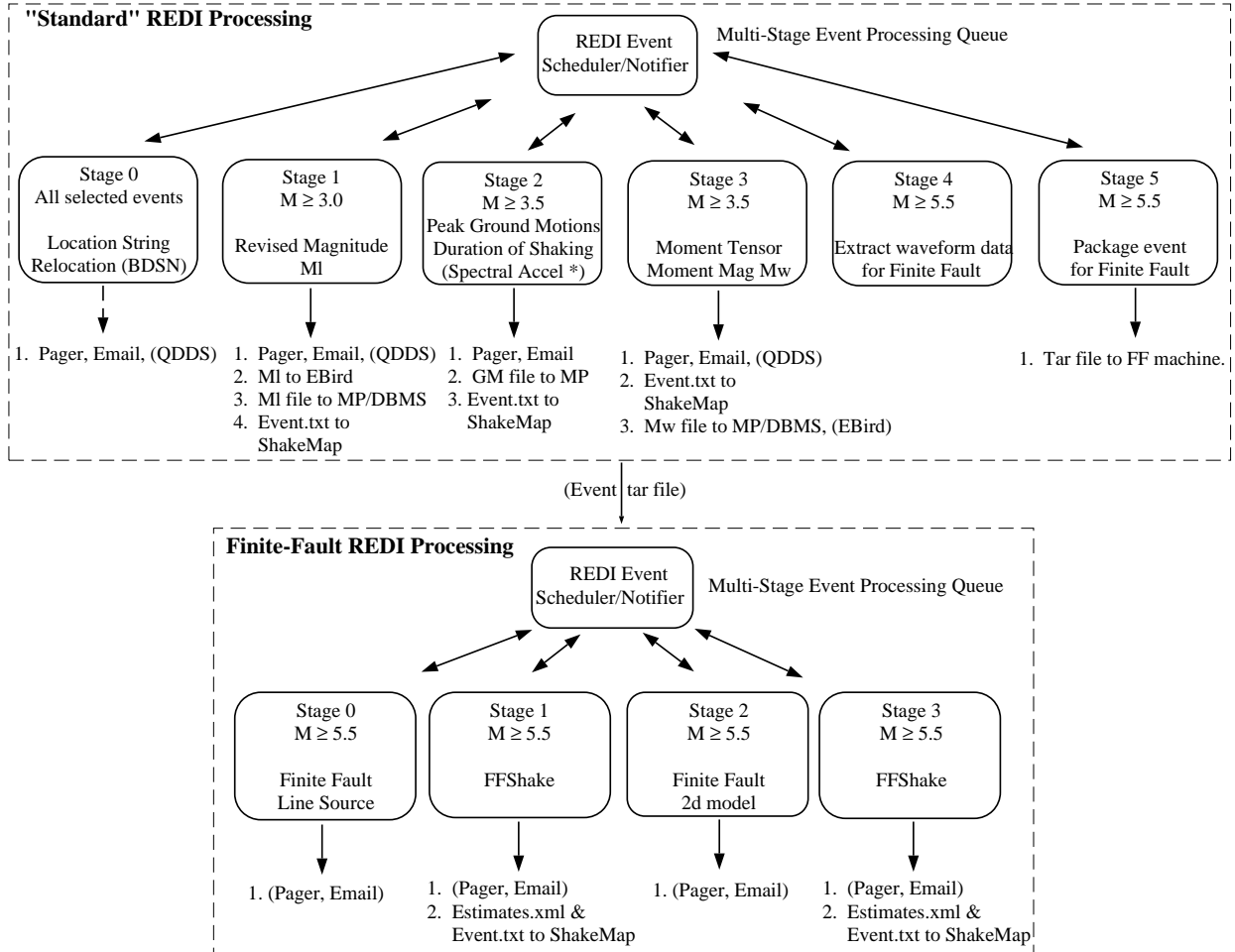2. Estimates.xml & Event.txt to ShakeMap

Figure 12.2: Diagram showing the two levels of REDI processing. The "Standard" processing is conducted on the two main data acquisition systems and includes the computation of $M_L$, ground-motion processing, and the determination of the seismic moment tensor. The "Finite-fault" system is an expansion of REDI processing. Items in parentheses are planned expansions.

tribution. As in Stage 1, "FFShake" computes peak ground acceleration, peak ground velocity, and spectral response at 0.3, 1.0, and 3.0 sec period for a grid of pseudo-stations in the vicinity of the epicenter and pushes these ground motions to the ShakeMap system.

## 2.3 ShakeMap

As part of the development of the finite-fault project, the BSL worked with the USGS Menlo Park to install ShakeMap V2.0 at UC Berkeley. Although USGS personnel had done most of the work to adapt the program to northern California, development was required to integrate the ShakeMap package into the REDI environment. In the process, BSL staff identified and fixed some minor bugs in the software.

The motivation for this effort is the desire to integrate the ground motions predicted from the finite-fault inversions into the ShakeMap generation. The goal is to provide updated ShakeMaps as more information about the earthquake source is available. Versions 2.0 and higher of ShakeMap are structured to allow the use of different "estimates" files, that is, to incorporate ground motions predicted by alternate means.

As shown in Figure 12.2, the REDI processing system is integrated with the ShakeMap software at several levels. "Event.txt" files are generated at several stages - these files tell the ShakeMap software to wake-up and process an event. A ShakeMap is generated following Stage 2 in the Standard processing and updated if a revised estimate of magnitude is obtained following Stage 3.

For events which trigger the finite-fault processing, estimates of ground motions based on the results of the line-source computation and the full 2D inversion are produced in the "FFShake" stages. "Estimates.xml" files are generated and pushed to the ShakeMap package. The output of the line source computation produces what we call an "Empirical ShakeMap", while output from the 2D inversion produces a "Conservative ShakeMap".

Figure 12.3 illustrates the three different methodologies with examples from an M6 earthquake which occurred in the Mammoth Lakes region in May 1999. Very few data were available to constrain these maps. This event is somewhat small for this methodology, but the impact of the successive improvements in the ground motion estimates is clearly illustrated.

Future plans include the continued testing and refinement of the procedure, working with the USGS group toward integration into the authoritative ShakeMap method for northern California and other regions, and development of additional capabilities based on the incorporation of BARD GPS data. Figure 12.4 shows the typical processing times associated with the current implementation.

## 2.4 Implementation

At present, two Earthworm-Earlybird systems in Menlo Park feed two "standard" REDI processing systems at UC Berkeley (Figure 12.1). One of these systems is the production or paging system; the other is set up as a hot backup. The second system is frequently used to test new software developments before migrating them to the production environment. The REDI finite-fault processing is installed on a third system, which is always "fed" from the production system. A fourth system is installed in Sacramento as a stand-alone operation in order to provide a redundant notification facility outside of the Bay Area.

This structure has greatly expedited automatic earthquake processing in northern California. The dense network and Earthworm-Earlybird processing environment of the NCSN provides rapid and accurate earthquake locations, low magnitude detection thresholds, and first-motion mechanisms for smaller quakes. The high dynamic range data loggers, digital telemetry, and broadband and strong-motion sensors of the BDSN and REDI analysis software provide reliable magnitude determination, moment tensor estimation, peak ground motions, and source rupture characteristics. Robust preliminary hypocenters are available about 25 seconds after the origin time, while preliminary coda magnitudes follow within 2-4 minutes. Estimates of local magnitude are generally available 30-120 seconds later, and other parameters, such as the peak ground acceleration and moment magnitude, follow within 1-4 minutes (Figure 12.4).

Earthquake information from the joint notification system is distributed by pager, e-mail, and the WWW. The first two mechanisms "push" the information to recipients, while the current Web interface requires interested parties to actively seek the information. Consequently, paging and, to a lesser extent, e-mail are the preferred methods for emergency response notification. The *recenteqs* site has enjoyed enormous popularity since its introduction and provides a valuable resource for information whose bandwidth exceeds the limits of wireless systems and for access to information which is useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

## 2.5 System Monitoring

In order to ensure that automatic systems are operating correctly, BSL staff and students participate in *alarm response*. Each week, two people are on duty in order to respond to earthquakes - or computer problems. One person is designated as primary and is responsible for earthquake-related issues. The second individual serves as a backup to the second and addresses more operational problems. For earthquake notification, the alarm response team receives pages from several sources including an automatic monitoring of the ground velocity at
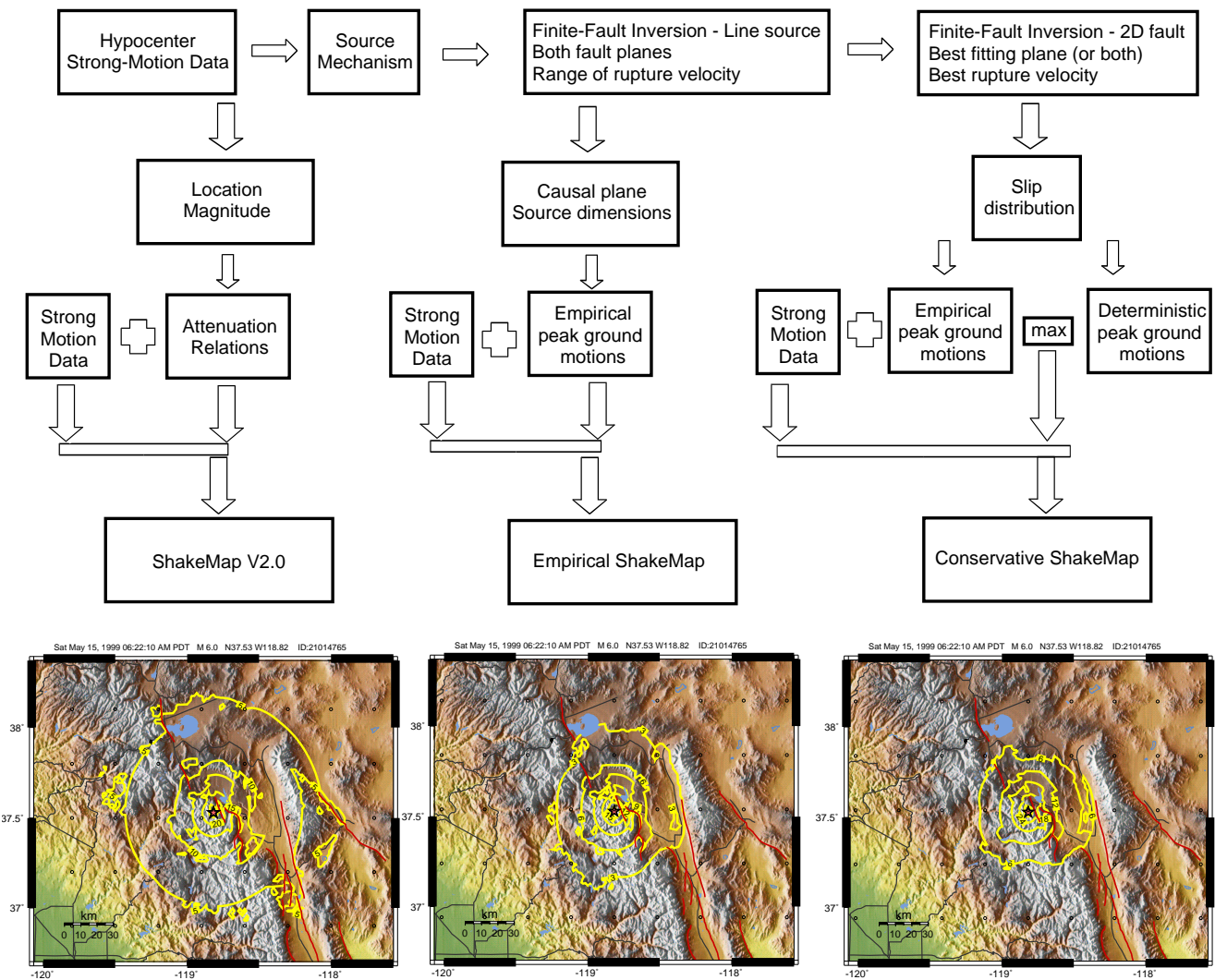
Figure 12.3: Summary of the three levels of ShakeMaps produced by the REDI system, with an example for an M6 earthquake in the Mammoth Lakes region. Note that the contour intervals vary from plot to plot.
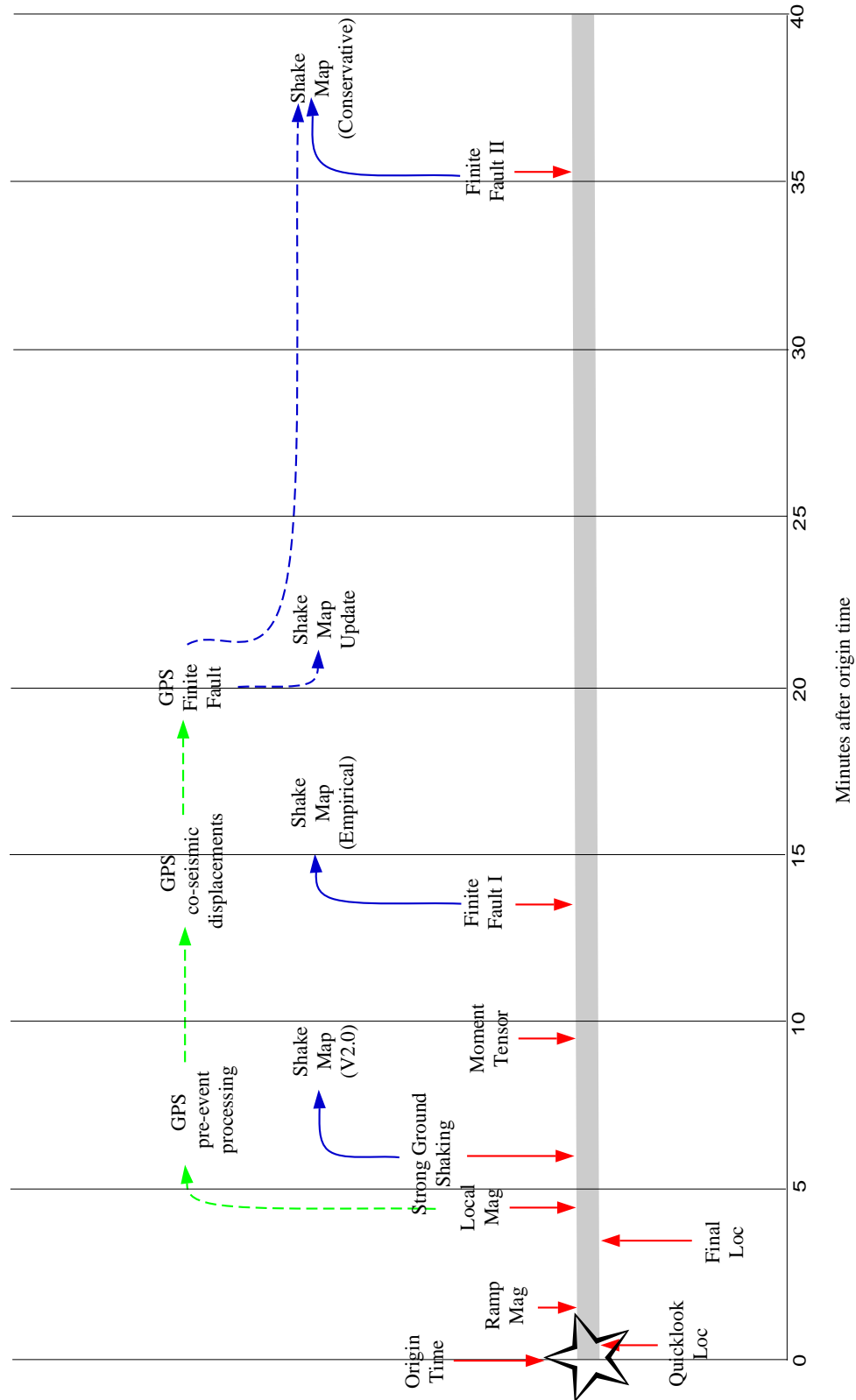
Figure 12.4: Illustration of the current (solid lines) and planned/proposed (dotted lines) development of real-time processing in northern California. The Finite Fault I and II are fully implemented within the REDI system at UC Berkeley and are integrated with ShakeMap. The resulting maps are still being evaluated and are not currently available to the public.

BKS (known as the SEismic ALarm or SEAL), a human-initiated alarm from the UCB Police Department, and separate notifications from REDI and the USGS. For operational monitoring, we have developed a component of the REDI system for tracking the heartbeats and data flow from critical systems and processes. Because this is inherently a distributed system, it is critical to monitor the "health" of every component. In the REDI system, the monitor program is a master scheduler that can perform several types of monitoring. As presently implemented, the monitor program watches critical computers and network components, disk resources, specified processes, and particular subsystems, such as data acquisition.

## 3. 2001-2002 Activities

### 3.1 Queueing of event messages

Working with the USGS, we have implemented a mechanism to queue event messages transmitted from the USGS to the REDI system. Previously, Earlybird opened a socket connection to the REDI computers. This approach was vulnerable to loss of data during times of connectivity problems. This socket-based approach has been replaced with a "file flinger", which provides the capability to queue or store event messages if connectivity between Berkeley and Menlo Park is lost.

### 3.2 Support for SNCL

Over the last year, we completed the implementation of full SEED channel names. In the past, the REDI system had used Station/Network/Channel (SNC) to describe a unique waveform channel. However, the evolution of the BDSN and experience with other networks led to the implementation of Location code or the full SNCL convention. This involved revisiting a number of REDI modules which handle waveform data.

This modification provided the opportunity to enhance the way REDI selects waveforms for processing. The "redi.avail" file allows for control of which channels are used for REDI modules and makes it easy to turn channels off and on if sensors or data loggers fail or telemetry problems are experienced.

### 3.3 Moment Tensor codes

As part of the changes for supporting SNCL, BSL staff put considerable time into recasting some of the moment tensor codes. Pete Lombard worked with Doug Dreger to modify the complete waveform codes. Changes included the ability to handle acceleration as well as velocity data, generalizing assumptions about data rates and channel orientation, and enhancements to how channels are selected, based on the distribution of stations.

### 3.4 $M_w$

The REDI system has routinely produced automatic estimates of moment magnitude ($M_w$) for many years. However, these estimates have not routinely used as the "official" magnitude, due in part to questions about the reliability of the automatic solutions. However, in response to the 05/14/2002 Gilroy earthquake ($M_w$ 4.9, $M_L$ 5.1) and the complications created by the publication of multiple magnitudes, the BSL and USGS Menlo Park have agreed to use automatically determined moment magnitudes, when available, to supplement estimates of local magnitude ($M_L$).

We have taken steps to use $M_w$ automatically and hope to complete this work in the early fall of 2002. In parallel, this work will allow both the USGS and the BSL components of the joint notification system to report earthquake information to Web independently (currently, only the USGS component distributes information to the Web using QDDS). As a result of this development, both the USGS and BSL components will distribute information to the Web, enhancing the robustness of the Northern California operations.

### 3.5 Collaboration with UNR

As part of our collaboration with UNR Seismological Laboratory, we implemented the capability to "forward" event messages from UNR over the REDI paging system in January. UNR sends Qpager format messages to the BSL via email, where a program extracts the message, evaluates the location, and then sends a page if the event is inside the UNR paging polygon. As part of this collaboration, the USGS Menlo Park and the BSL modified their paging polygon to align with the California/Nevada border.

### 3.6 ShakeMap

During 2001-2002, the ShakeMap software at the BSL was upgraded to version 2.4, in order to stay synchronized with the implementation in Menlo Park. V2.5 is currently being tested in Menlo Park and we anticipate upgrading in the next quarter.

### 3.7 Northern California Management Center

As part of ongoing efforts to improve the monitoring systems in northern California, the BSL and the USGS Menlo Park have begun to plan for the next generation of the northern California joint notification system.

Figure 12.1 illustrates the current organization of the two systems. As described above, an Earthworm/Earlybird component is tied to a REDI component and the pair form a single "joint notification system". Although this approach has functioned reasonably well over the last 5 years, there are a number of potential problems

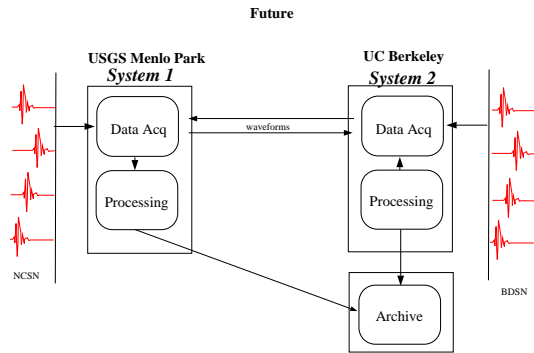**Northern California Earthquake Notification System**

**Future**



Figure 12.5: Future design of the Northern California Earthquake Notification System. In contrast with the current situation (Figure 12.1), the system is being re-designed to integrate the Earthworm/Earlybird/REDI software into a single package. Parallel systems will be run at the Berkeley and Menlo Park facilities of the Northern California Operations Center.



Figure 12.6: Illustration of the design currently being considered for the development of the Northern California Management Center.

associated with the separation of critical system elements by 30 miles of San Francisco Bay.

Recognizing this, we intend to redesign the northern California operations so that a single independent system operates at the USGS and at UC Berkeley. Figures 12.5 and 12.6 illustrate the planned configuration. Our discussions have proceeded to the stage of establishing specifications and determining the details required for design. In the last year, the BSL and the USGS Menlo Park have met several times to discuss designs for the proposed system. In October, the BSL and the USGS Menlo Park asked representatives from the USGS Golden, USGS Pasadena, and Caltech to participate in a 2-day meeting.

## 4.    Routine Earthquake Analysis

On a daily basis, the BSL continues to locate and determine the magnitude of earthquakes in northern California and adjacent regions. As a general rule, events are analyzed if their magnitude is greater than 2.8 in the Central Coast ranges, greater than 3.0 in all of northern California, or greater than 3.8 in the bordering regions. Traditionally, these events were located using hand-picked arrival times from the BDSN stations in conjunction with P-arrival times from the NCSN using the program strelp. Over the past several years, the BSL has made a transition in the daily analysis to take advantage of the automatic processing system. As part of this transition, events which have been processed by the automatic system are not generally relocated, although phase arrivals are still hand-picked and the synthetic Wood-Anderson
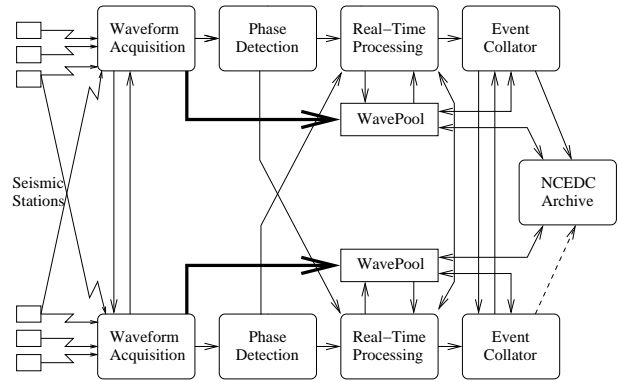
readings are checked. Instead, analysts are focusing on the determination of additional parameters, such as the seismic moment tensor, phase azimuth, and measures of strong ground shaking.

From July 2001 through June 2002, BSL analysts reviewed nearly 200 earthquakes in northern California and adjoining areas, ranging from M2.8 to 5.9. Reviewed moment tensor solutions were obtained for 28 events (through 6/30/2002). Figure 12.7 and Table 12.1 displays the earthquakes located in the BSL catalog and the moment tensor solutions.

In addition to the routine analysis of local and regional earthquakes, the BSL also processes teleseismic earthquakes. Taking advantage of the CNSS catalog, analysts review teleseisms of magnitude 5.8 and higher. All events of magnitude 6 and higher are read on the quietest BDSN station, while events of magnitude 6.5 and higher are read on the quietest station and BKS. Earthquakes of magnitude 7 and higher are read on all BDSN stations.

The locations and magnitude determined by the BSL are cataloged on the NCEDC. The phase and amplitude data are provided to the NEIC, along with the locations and magnitudes, as contributions to the global catalogs, such as that of the ISC.
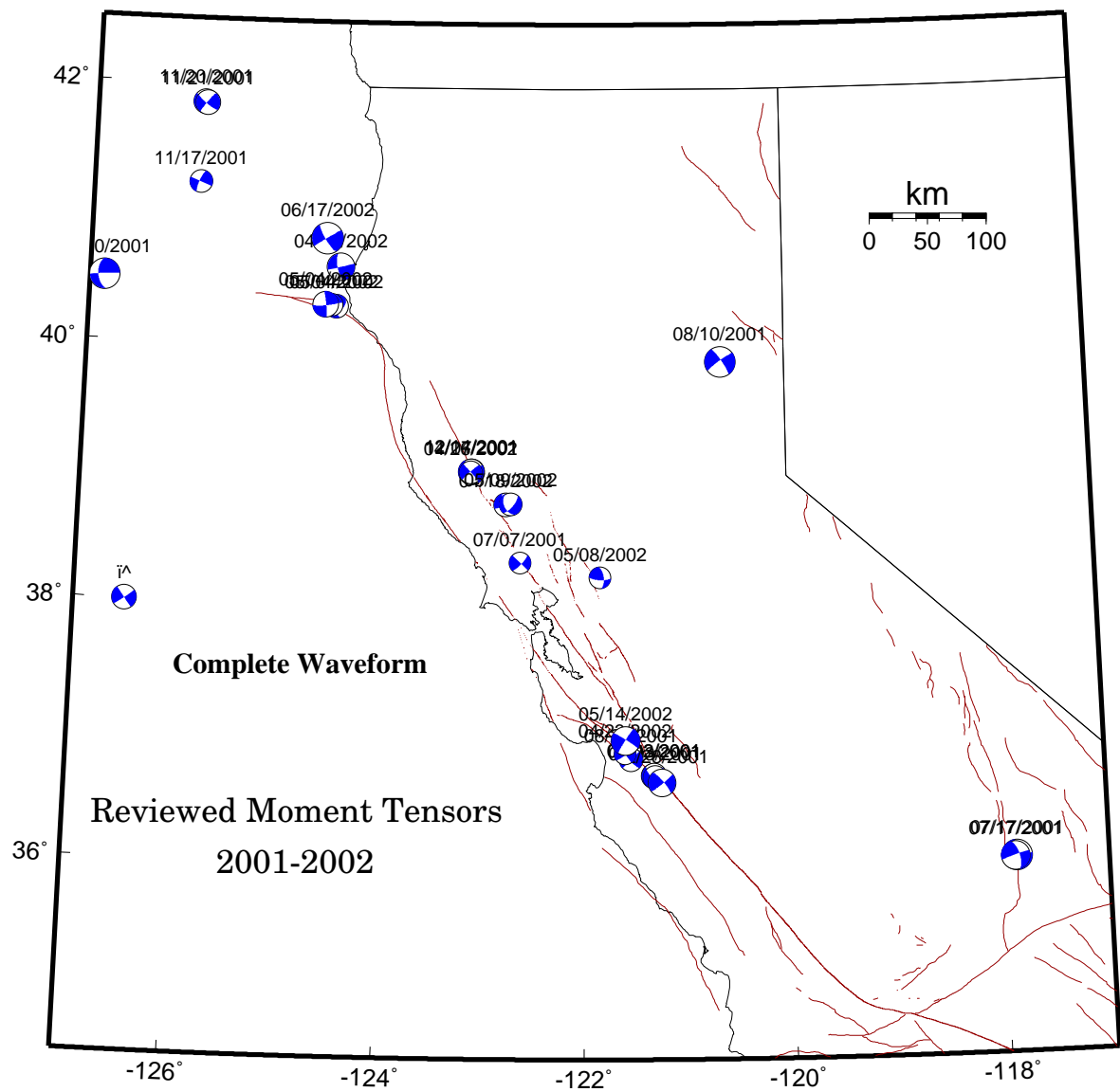
## 5.    Acknowledgements

Figure 12.7: Map comparing the reviewed moment tensor solutions from the joint notification system. Solutions from the complete waveform inversion are plotted in black.

| Location | Date | Time | Lat. | Lon. | MT Dep. | $M_L$ | $M_w$ | $M_o$ | Str. | Dip | Rake | Meth. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tres Pinos | 07/02/2001 | 17:33:53.0 | 36.694 | -121.333 | 8.0 | 4.1 | 4.1 | 1.80e22 | 60 | 89 | -6 | 1 |
| | | | | | 11.0 | 4.1 | 4.1 | 1.69e22 | 133 | 87 | -158 | 2 |
| Tres Pinos | 07/03/2001 | 19:02:50.0 | 36.696 | -121.329 | 6.0 | 4 | 4.2 | 2.30e22 | 221 | 85 | 28 | 1 |
| | | | | | 11.0 | 4 | 4.1 | 2.05e22 | 138 | 77 | -176 | 2 |
| Tres Pinos | 07/03/2001 | 19:07:16.0 | 36.683 | -121.319 | 6.0 | 3.9 | 4.0 | 1.10e22 | 36 | 70 | -35 | 1 |
| | | | | | 11.0 | 3.9 | 4.0 | 1.23e22 | 133 | 76 | -154 | 2 |
| Rohnert Park | 07/07/2001 | 15:07:31.0 | 38.344 | -122.630 | 11.0 | 3.7 | 3.7 | 3.34e21 | 133 | 90 | -166 | 2 |
| Coso Junction | 07/17/2001 | 12:07:25.0 | 36.017 | -117.878 | 8.0 | 4.9 | 5.2 | 6.89e23 | 352 | 83 | 171 | 2 |
| Coso Junction | 07/17/2001 | 12:59:58.0 | 36.013 | -117.893 | 5.0 | 4.7 | 4.9 | 2.76e23 | 344 | 66 | -176 | 2 |
| Portola | 08/10/2001 | 20:19:26.0 | 39.893 | -120.638 | 24.0 | 5.1 | 5.1 | 4.60e23 | 139 | 89 | 161 | 1 |
| | | | | | 24.0 | 5.1 | 5.2 | 6.80e23 | 326 | 81 | -173 | 2 |
| San Benito | 08/26/2001 | 05:03:02.0 | 36.820 | -121.550 | 5.0 | 3.9 | 4.0 | 1.12e22 | 135 | 80 | -179 | 2 |
| Trinidad | 11/17/2001 | 02:17:00.0 | 41.234 | -125.915 | 21.0 | 3.8 | 3.9 | 8.18e21 | 292 | 90 | -167 | 2 |
| Oregon | 11/20/2001 | 16:58:11.0 | 41.854 | -125.900 | 24.0 | 3.8 | 4.1 | 1.40e22 | 225 | 74 | 13 | 2 |
| Oregon | 11/21/2001 | 02:01:28.0 | 41.844 | -125.878 | 24.0 | 3.9 | 4.1 | 1.48e22 | 218 | 84 | 10 | 2 |
| Punta Gorda | 11/30/2001 | 07:46:56.0 | 40.490 | -126.850 | 18.0 | 4.7 | 4.9 | 2.20e23 | 269 | 79 | 145 | 1 |
| | | | | | 11.0 | 4.7 | 5.1 | 4.69e23 | 265 | 88 | -144 | 2 |
| Ukiah | 12/07/2001 | 14:29:08.0 | 39.043 | -123.117 | 8.0 | 4.1 | 4.3 | 3.09e22 | 326 | 81 | 162 | 2 |
| Ukiah | 12/14/2001 | 09:41:05.0 | 39.045 | -123.120 | 11.0 | 4 | 4.4 | 3.92e22 | 328 | 76 | 179 | 2 |
| Tres Pinos | 12/28/2001 | 21:14:01.0 | 36.641 | -121.252 | 5.0 | 4.7 | 4.6 | 9.99e22 | 320 | 80 | 174 | 2 |
| Punta Gorda | 01/07/2002 | 20:23:15.0 | 40.309 | -127.108 | 11.0 | 4.7 | 5.0 | 3.38e23 | 345 | 72 | -79 | 2 |
| Geysers | 04/18/2002 | 11:35:40.0 | 38.791 | -122.774 | 5.0 | 3.5 | 4.0 | 9.97e21 | 162 | 74 | -175 | 2 |
| San Jose | 04/23/2002 | 11:59:20.0 | 36.866 | -121.607 | 8.0 | 3.6 | 3.7 | 3.45e21 | 324 | 89 | 171 | 2 |
| Ukiah | 04/26/2002 | 11:01:26.0 | 39.040 | -123.125 | 8.0 | 3.5 | 3.8 | 5.48e21 | 228 | 85 | -2 | 2 |
| Ferndale | 04/29/2002 | 00:43:29.0 | 40.609 | -124.462 | 27.0 | 4.4 | 4.6 | 1.00e23 | 166 | 68 | 179 | 2 |
| Punta Gorda | 05/04/2002 | 12:17:00.0 | 40.305 | -124.501 | 5.0 | 3.9 | 4.0 | 9.85e21 | 160 | 73 | 44 | 2 |
| Punta Gorda | 05/04/2002 | 12:54:23.0 | 40.313 | -124.549 | 8.0 | 3.7 | 3.8 | 5.69e21 | 347 | 74 | 2 | 2 |
| Punta Gorda | 05/04/2002 | 13:56:31.0 | 40.319 | -124.611 | 5.0 | 4.3 | 4.4 | 4.54e22 | 353 | 85 | -8 | 2 |
| Fairfield | 05/08/2002 | 14:59:36.0 | 38.229 | -121.845 | 14.0 | 3.7 | 3.7 | 3.90e21 | 353 | 62 | 160 | 2 |
| Geysers | 05/09/2002 | 11:07:55.0 | 38.797 | -122.728 | 5.0 | 3.6 | 3.9 | 8.11e21 | 155 | 43 | -147 | 2 |
| Gilroy | 05/14/2002 | 05:00:29.0 | 36.967 | -121.600 | 8.0 | 5.2 | 4.9 | 2.86e23 | 212 | 87 | -6 | 2 |
| Nevada | 06/14/2002 | 12:40:49.0 | 36.715 | -116.300 | 8.0 | 4.4 | 4.6 | 7.86e22 | 2 | 75 | -121 | 2 |
| Eureka | 06/17/2002 | 16:55:07.0 | 40.829 | -124.606 | 21.0 | 5.1 | 5.3 | 8.98e23 | 238 | 88 | 12 | 2 |

Table 12.1: Moment tensor solutions for significant events from July 1, 2001 to June 30, 2002 using both regional methodologies. Epicentral information from the UC Berkeley/USGS Northern California Earthquake Data Center. Moment is in dyne-cm and depth is in km. Key to methods: (1) Complete waveform fitting inversion; (2) Regional surface wave inversion.

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# Chapter 13

# Northern California Earthquake Data Center

## 1. Introduction

The Northern California Earthquake Data Center, a joint project of the Berkeley Seismological Laboratory and the U.S. Geological Survey at Menlo Park, serves as an "on-line" archive for various types of digital data relating to earthquakes in central and northern California. The NCEDC is located at the Berkeley Seismological Laboratory, and has been accessible to users via the Internet since mid-1992.

The primary goal of the NCEDC is to provide a stable and permanent archival and distribution center of digital geophysical data for northern and central California such as seismic waveforms, electromagnetic data, GPS data, and earthquake parametric data. The principal networks contributing seismic data to the data center are the Berkeley Digital Seismic Network (BDSN) operated by the Seismological Laboratory, the Northern California Seismic Network (NCSN) operated by the USGS, and the Bay Area Regional Deformation (BARD) GPS network. The collection of NCSN digital waveforms date from 1984 to the present, the BDSN digital waveforms date from 1987 to the present, and the BARD GPS data date from 1993 to the present.

The NCEDC continues to use the World Wide Web as a principal interface for users to request, search, and receive data from the NCEDC. The NCEDC has implemented a number of useful and original mechanisms of data search and retrieval using the World Wide Web, which are available to anyone on the Internet. All of the documentation about the NCEDC, including the research users' guide, is available via the Web. Users can perform catalog searches and retrieve hypocentral information and phase readings from the various earthquake catalogs at the NCEDC via easy-to-use forms on the Web. In addition, users can peruse the index of available broadband data at the NCEDC, and can request and retrieve broadband data in standard SEED format via the Web. Access to all datasets is available via research accounts at the NCEDC. The NCEDC's Web address is

```
http://quake.geo.berkeley.edu/
```

## 2. NCEDC Overview

The NCEDC is located within the computing facilities at the Berkeley Seismological Laboratory in McCone Hall. The BSL facility provides the NCEDC with air conditioning, 100 bit switched network, and reliable power from a UPS with generator backup.

The current NCEDC facilities consist of a Sun Ultra 450 computer, a 2.5 TByte capacity DISC 517 slot jukebox with four 5.2 GByte MO drives and 5.2 GB MO media, an 15-slot AIT tape jukebox which holds 25 GBytes per tape, and the SAM-FS hierarchical storage management (HSM) software. A dual processor Sun Ultra 60 provides Web services and research account access to the NCEDC.

The hardware and software system can be configured to automatically create multiple copies of each data file. The NCEDC uses this feature to create an online copy of each data file on MO media, and another copy on AIT tape which is stored offline.

## 3. 2001-2002 Activities

By its nature, data archiving is an ongoing activity. In 2001-2002, the NCEDC continued to expand its data holdings and enhance access to the data. Projects and activities of particular note include:

- Establishment of a continuous archive for NCSN broadband data

- Development of procedures to populate NCSN hardware information, instrument response, and waveform inventory in the NCEDC database

- Development of *CalQC* program to facilitate quality control procedures for continuous data channels

- Design of waveform protocol to exchange data with the SCEDC

- Adaption of *STP* to the NCEDC

- Initiation of project to archive the remaining 16-bit BDSN data to MiniSEED

- Development of new Web pages

These activities and projects are described in detail below.

# 4. Data Collections

The bulk of the data at the NCEDC consist of waveform and GPS data from northern California. The total size of the datasets archived at the NCEDC is shown in Table 13.1. Figure 13.1 shows the geographic distribution of data archived by the NCEDC.

## 4.1 BDSN/NHFN/MPBO Seismic Data

The archival of current BDSN (Chapter 4), NHFN (Chapter 5), and Mini-PBO (Chapter 9) (all stations using the network code BK) seismic data is an ongoing task. These data are telemetered from more than 30 seismic data loggers in real-time to the BSL, where they are written to disk files. Each day, an extraction process creates a daily archive by retrieving all continuous and event-triggered data for the previous day. The daily archive is run through quality control procedures to correct any timing errors, triggered data is reselected based on the REDI, NCSN, and BSL earthquake catalogs, and the resulting daily collection of data is archived at the NCEDC.

All of the data acquired from the BDSN/NHFN/MPBO Quanterra data loggers are archived at the NCEDC. The NCEDC has made an effort to archive older digital data, and the 16-bit BDSN digital broadband data from 1987-1991 have been converted to MiniSEED and are now online. In late June 2002, the NCEDC initiated a project to convert the remaining 16-bit BDSN data (MHC, SAO, and PKD1) from late 1991 through mid-1992 to MiniSEED. An undergraduate student has been hired to read the old tapes and to work on the conversion. Data acquired by portable 24-bit RefTek recorders before the installation of Quanterra data loggers at NHFN sites has not yet been converted to MiniSEED and archived.

## 4.2 NCSN/SHFN Seismic Data

NCSN and SHFN waveform data are sent to the NCEDC via the Internet. The NCSN event waveform files are automatically transferred from the Menlo Park to the NCEDC as part of the routine analysis procedure by the USGS, and are automatically verified and archived by the NCEDC.

A few corrupt NCSN event files were discovered at the NCEDC several years ago, and were eventually traced down to suspected flaws in the 12-inch WORM media and/or firmware problems on the Sony WDA-600 series jukeboxes used by the NCEDC. When we transcribed the data from the 12-inch WORM media to the current 5.25 inch magneto-optical media, we verified that all files were transcribed accurately. In 2000-2001, using software developed at the NCEDC to detect possibly corrupt NCSN files, we identified 4704 possibly corrupted NCSN waveform event files. We re-read the original NCSN tapes for all of these events, discovered that only 71 of the files were actually corrupt, and replaced the corrupted event waveform files.

The NCEDC maintains a list of teleseismic events recorded by the NCSN, which is updated automatically whenever a new NCSN event file is received at the NCEDC, since these events do not appear in the NCSN catalog.

The NCSN has installed 9 continuously telemetered digital broadband stations in northwest California and southwest Oregon in support of the USGS/NOAA Consolitated Reporting of EarthquakeS and Tsunamis (CREST) system. This year, the NCEDC established proceedures to create an archive of continuous data from these stations, in addition to the event waveform files. These data initially included channels at 50 and 100 Hz, but now are all 100 Hz sampling. The NCEDC hoped to generate an archive of 20 Hz data (for consistency with the BDSN data) from these 100 Hz waveforms, but problems with missing data has made this difficult. At this point, the NCEDC is archiving the 100 Hz data without decimation.

## 4.3 Parkfield HRSN Data

Event seismograms from the Parkfield High Resolution Seismic Network (HRSN) from 1987 through June 1998 are available in their raw SEGY format via NCEDC research accounts. A number of events have faulty timing due to the lack or failure of a precision timesource for the network. Due to funding limitations, there is currently no ongoing work to correct the timing problems in the older events or to create MiniSEED volumes for these events. However, a preliminary catalog for a significant number of these events has been constructed, and the catalog is available via the web at the NCEDC.

As described in Chapter 6, the original HRSN acquisition system died in late 1998, and an interim system of portable RefTek recorders were installed at some of the sites. Data from this interim system are not currently available online.

In 2000 and 2001, 3 new borehole sites were installed, and the network was upgraded to operate with Quan-
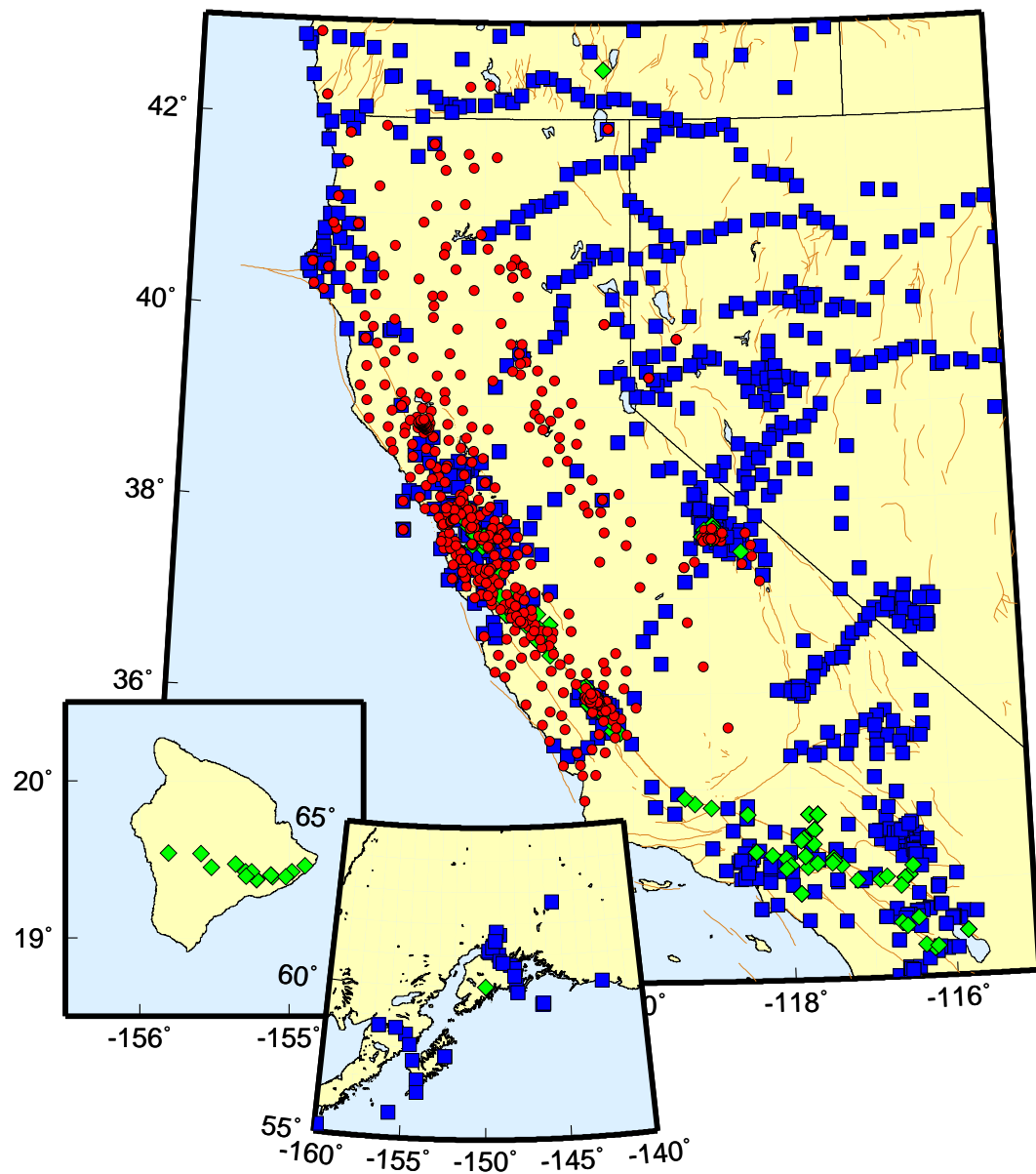
Figure 13.1: Map showing the location of stations whose data are archived at the NCEDC. Circles are seismic sites; squares are GPS sites, and diamonds are the locations of USGS Low-frequency experiments.
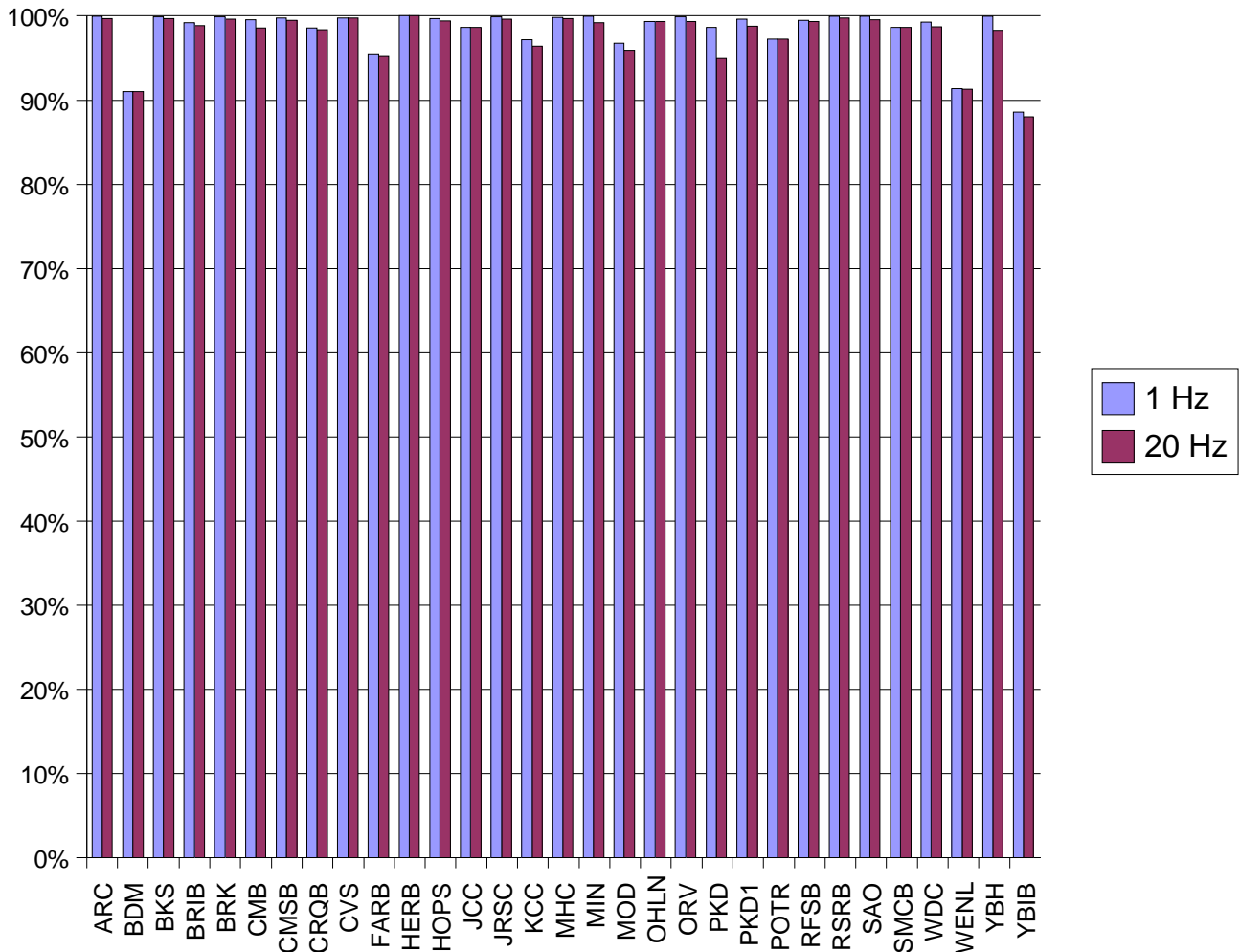
# BDSN/NHFN Data Availability



Figure 13.2: Chart showing the availability of BDSN/NHFN/MPBO data at the NCEDC for the 1 Hz and 20 Hz channels from 01/01/1996 - 06/30/2002. The "uptime" of these networks is better than 95% at nearly all stations. Exceptions are BDM (damaged by a lightning strike in May 2000), FARB (power problems when the USFWS generator failed in 1998), MOD (the newest BDSN station which suffered some delays during installation), WENL (flooded during the winter of 1997), and YBIB (damaged during a lightning strike in 1997, and without AC power for the past 2 years). In general, a difference between the 1 and 20 Hz data is indicative of one or more significant telemetry problems. Following a major telemetry outage, BSL staff will recover 1 Hz continuous data but only event data for the 20 Hz channels.

| Data Type | MBytes |
|---|---|
| BDSN/NHFN/MPBO (broadband, electric field, magnetic field, strain) waveforms | 848,181 |
| NCSN seismograms | 328,467 |
| Parkfield HRSN seismograms | 352,860 |
| BARD GPS (RINEX and raw data) | 296,172 |
| UNR Nevada seismograms | 85,778 |
| Calpine/Unocal Geysers region seismograms | 38,658 |
| USGS Low frequency geophysical waveforms | 917 |
| Misc data | 56,802 |
| Total size of archived data | 2,007,835 |

Table 13.1: Volume of Data Archived at the NCEDC by network

terra Q730 data loggers and digital telemetry. The upgraded acquisition system detects events using the HRSN stations, and through collaboration with the temporarily deployed PASSCAL network (PASO), extracts waveforms from both the HRSN and the PASO stations. The event waveform files are automatically transferred to the NCEDC, where thet are made available to the research community via anonymous ftp until they are reviewed and permanently archived.

The HRSN 20 Hz (BP) and state-of-health channels are being archived continuously at the NCEDC. As an interim measure, the NCEDC is also archiving continuous data from the 250 Hz (DP) channels in order to help researchers retrieve events that were not detected during the network upgrade.

## 4.4 UNR Broadband data

The University of Reno in Nevada (UNR) operates several broadband stations in western Nevada and eastern California that are important for northern California earthquake processing and analysis. Starting in August 2000, the NCEDC has been receiving and archiving continuous broadband data from four UNR stations. The data are transmitted in real-time from UNR to UC Berkeley, where it is made available for real-time earthquake processing and for archiving.

In a situation similar to that of the broadband waveforms from the NCSN, the NCEDC originally planned to create an archive of 20 Hz data from the 100 Hz data. However, frequent gaps in the data complicate the development of a robust decimation process. At this time, the UNR broadband waveforms are being archived at 100 Hz.

## 4.5 Electro-Magnetic Data

The NCEDC continues to archive and process electric and magnetic field data acquired from data loggers at two sites (SAO and PKD). At PKD and SAO, 3 components of magnetic field and 2 or 4 components of electric field are digitized and telemetered in real-time along with

seismic data to the Seismological Laboratory, where they are processed and archived at the NCEDC in a similar fashion to the seismic data (Chapter 7). The system generates continuous data channels at 40 Hz, 1 Hz, and .1 Hz for each component of data. All of these data are archived and remain available online at the NCEDC. Using programs developed by Dr. Martin Fullerkrug at the Stanford University STAR Laboratory (now at the Institute for Meteorology and Geophysics at the Univerity of Frankfurt), the NCEDC is computing and archiving magnetic activity and Schumann resonance analysis using the 40 Hz data from this dataset. The magnetic activity and Schumann resonance data can be accessed from the Web.

In addition to the electro-magnetic data from PKD and SAO, the NCEDC archives data from a low-frequency, long-baseline electric field project operated by Dr. Steve Park of UC Riverside at site PKD2. This experiment (which is separate from the equipment at PKD1 described in Chapter 7), uses an 8-channel Quanterra data logger to record the data, which are transmitted to the BSL using the same circuit as the BDSN seismic data. These data is acquired and archived in an identical manner to the other electric field data at the NCEDC.

## 4.6 GPS Data

The NCEDC continues to expand its archive of GPS data through the BARD (Bay Area Regional Deformation) network of continuously monitored GPS receivers in northern California (Chapter 8). The NCEDC GPS archive now includes 67 continuous sites in northern California. There are approximately 50 core BARD sites owned and operated by UC Berkeley, USGS (Menlo Park and Cascade Volcano Observatory), LLNL, UC Davis, UC Santa Cruz, Trimble Navigation, and Stanford. Data are also archived from sites operated by other agencies including East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, and the Jet Propulsion Laboratory.

This year the NCEDC continued to archive noncontinuous survey GPS data. The initial dataset to be

archived is the survey GPS data collected by the USGS Menlo Park for northern California and other locations. The NCEDC is the principal archive for this dataset. Significant quality control efforts were implemented by the NCEDC to ensure that the raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS MP GPS data has been transferred to the NCEDC and virtually all of the data from 1992 to the present has been archived and is available for distribution.

## 4.7 Calpine/Unocal Geysers Seismic Data

The Calpine Corporation currently operates a microseismic monitoring network in the Geysers regions of northern California. Prior to 1999 this network was operated by Unocal. Through various agreements with both Unocal and Calpine, the companies have release triggered event waveform data from 1989 to through 2000 along with and preliminary event catalogs for the same time period for archiving and distribution through the NCEDC. This dataset represents over 296,000 events that were recorded by Calpine/Unocal Geysers network, and are available via research accounts at the NCEDC.

## 4.8 USGS Low Frequency Data

Over the last 26 years, the USGS at Menlo Park, in collaboration with other principal investigators, has collected an extensive low-frequency geophysical data set that contains over 1300 channels of tilt, tensor strain, dilatational strain, creep, magnetic field, water level, and auxilliary channels such as temperature, pore pressure, rain and snow accumulation, and wind speed. In collaboration with the USGS, we assembled the requisite information for the hardware representation of the stations and the instrument responses for many channels of this diverse dataset, and developed the required programs to populate and update the hardware database and generate the instrument responses. We developed the programs and procedures to automate the process of importing the raw waveform data and convert it to MiniSEED format.

We have currently archived timeseries data from 887 data channels from 167 sites, and have instrument response information for 542 channels at 139 sites. The waveform archive is updated on a daily basis with data from 350 currently operating data channels. We will augment the raw data archive as additional instrument response information is assembled for the channels, and will work with the USGS to clearly define the attributes of the "processed" data channels.

## 4.9 Earthquake Catalogs

### Northern California

Currently both the USGS and BSL construct and maintain earthquake catalogs for northern and central California. The "official" UC Berkeley earthquake catalog begins in 1910, and the USGS "official" catalog begins in 1966. Both of these catalogs are archived and available through the NCEDC, but the existence of 2 catalogs has caused confusion among both researchers and the public. The BSL and the USGS have spent considerable effort over the past year to define procedures for merging the data from the two catalogs into a single northern and central California earthquake catalog in order to present a unified view of northern California seismicity. The differences in time period, variations in data availability, and mismatches in regions of coverage all complicate the task.

### Worldwide

The NCEDC, in conjunction with the Council of the National Seismic System (CNSS), has producing and distributed a world-wide composite catalog of earthquakes based on the catalogs of the national and various U.S. regional networks for several years. Each network updates their earthquake catalog on a daily basis at the NCEDC, and the NCEDC constructs a composite world-wide earthquake catalog by combining the data, removing duplicate entries that may occur from multiple networks recording an event, and giving priority to the data from each network's *authoritative region*. The catalog, which includes data from 14 regional and national networks, is searchable using a Web interface at the NCEDC. The catalog is also freely available to anyone via ftp over the Internet.

With the demise of the CNSS and the development of the ANSS, the NCEDC has been asked to update the Web pages to present the composite catalog as a product of the ANSS. This conversion will be completed in the fall of 2002.

## 5. Data Quality Control

The NCEDC developed a GUI-based state-driven system *CalQC* to facilitate the quality control processing that is applied to the BK, NC broadband, NN, and BP data sets.

The quality control procedures for these datasets include the following tasks:

- data extraction of a full day of data,

- quickcheck program to summarize the quality and stability of the stations' clock,

- checks for missing data along with procedures to retrieve data from the stations and incorporate it into the day of data,

- optional creation of multi-day timeseries plots for state-of-health data channels,

- optional timing corrections for data,

- optional extraction of event-based waveforms from continuous data channels,

- optional repacking of MiniSEED data,

- creating waveform inventory entries in the NCEDC database,

- publishing the data for remote access on the NCEDC.

*CalQC* uses previously developed the programs to perform each function, but it provides a graphical point-and-click interface to automate these procedures, and to provide the analyst with a record of when each process was started, whether it executed correctly, and whether the analyst has indicated that a step has been completed.

# 6.    Database Development

Most of the parametric data archived at the NCEDC, such as earthquake catalogs, phase and amplitude readings, waveform inventory, and instrument responses have been stored in flat text files. Flat file are easily stored and viewed, but are not efficiently searched. Over the last year, the NCEDC, in collaboration with the USGS/SCEC Data Center, and TriNet, has continued development of database schemas to store the parametric data from the joint earthquake catalog, station history, complete instrument response for all data channels, and waveform inventory.

The parametric schema supports tables and associations for the joint earthquake catalog. It allows for multiple hypocenters per event, multiple magnitudes per hypocenter, and association of phases and amplitudes with multiple versions of hypocenters and magnitudes respectively. The instrument response schema represents full multi-stage instrument responses (including filter coefficients) for the broadband data loggers. The hardware tracking schema will represent the interconnection of instruments, amplifiers, filters, and data loggers over time. This schema will be used to store the joint northern California earthquake catalog and the CNSS composite catalog.

The entire description for the BDSN/NHFN/MPBO, HRSN, and USGS Low Frequency Geophysical networks and data archive has been entered into the hardware tracking, SEED instrument response, and waveform tables. Programs have been developed to perform queries of waveform inventory and instrument responses, and the NCEDC can now generate full SEED volumes from the BDSN network based on information from the database and the waveforms on the mass storage system. The second stage of development will include the NCSN waveform inventory and later the NCSN instrument response data as they are made available. We distributed all of our programs and procedures to populate the hardware tracking and instrument response tables to the SCEDC in order to help them populate their database.

Additional details on the joint catalog effort and database schema development may be found at `http://quake.geo.berkeley.edu/db`

# 7.    Data Access & Distribution

The various earthquake catalogs, phase, and earthquake mechanism can be searched using NCEDC web interfaces that allow users to select the catalog, attributes such as geographical region, time and magnitude. The GPS data is available to all users via anonymous ftp. Research accounts are available to any qualified researcher who needs access to the other datasets that currently are not available via the Web.

## 7.1    SeismiQuery

During 2000 and 2001, the NCEDC has developed a generalized database query system to support the development of portable database query applications among data centers with different internal database schemas. The initial goal was to modify the IRIS SeismiQuery web interface program to make installation easier at the NCEDC and other data centers, as well as to introduce a new query language that would be schema independent.

In order to support SeismiQuery and other future database query applications, we defined a set of Generic Data Views (GDV) for the database that encompassed the basic objects that we expect most data centers to support. We introduced a new language we call MSQL (Meta SeismiQuery Language), which is based on generic SQL, and uses the GDV's for its core schema. MSQL queries are converted to Data Center specific SQL queries by the parsing program MSQL2SQL. This parser stores the MSQL parsing tree in a data structure and API's were implemented to browse and modify elements in the parsing tree. These API's are the only datacenter or database specific source codes. We finally modified the SeismiQuery web interface to uniformly generate MSQL requests and to process these requests in a consistent fashion.

We have installed SeismiQuery at the NCEDC, where it provides a common interface for querying attributes

and available data for SEED format data, and have provided both IRIS and the SCEC Data Center with our modified version of SeismiQuery. We envision using this approach to support other database query programs in the future.

## 7.2 NetDC

In a collaborative project with the IRIS DMC and other worldwide datacenters, the NCEDC helped develop and implement NetDC, a protocol which will provide a seamless user interface to multiple datacenters for geophysical network and station inventory, instrument responses, and data retrieval requests. The NetDC builds upon the foundation and concepts of the IRIS BREQ_FAST data request system. The NetDC system was put into production in January 2000, and is currently operational at three datacenters worldwide – the NCEDC, IRIS DMC, and Geoscope. The NetDC system receives user requests via email, automatically routes the appropriate portion of the requests to the appropriate datacenter, optionally aggregates the responses from the various datacenters, and delivers the data (or ftp pointers to the data) to the users via email.

The NCEDC hosts a web page that allows users to easily query the NCEDC waveform inventory, generate and submit NetDC requests to the NCEDC. The NCEDC currently supports both the BREQ_FAST and NetDC request formats. As part of our collaboration with SCEDC, the NCEDC provided its BREQ_FAST interface code to SCEDC, have worked closely with them to implement BREQ_FAST requests at the SCEDC.

## 7.3 STP

This year, the NCEDC wrote a collaborative proposal with the SCEDC to the Southern California Earthquake Center, with the goal of unifying data access between the two data centers. As part of this project, the NCEDC and SCEDC are working to support a common set of 3 tools for accessing waveform and parametric data: SeismiQuery, NetDC, and STP.

The Seismogram Transfer Program or STP is a GUI-based client-server program, developed at at the SCEDC. Access to STP is either through a simple direct interface that is available for Sun or Linux platforms or through a Web interface. With the direct interface, the data are placed directly on a users' computer in several possible formats, with the byte-swap conversion performed automatically. With the Web interface, the selected and converted data are retrieved with a single ftp command. The STP interface also allows rapid access to parametric data such as hypocenters and phases.

The NCEDC has started implementing STP, working with the SCEDC on extensions and needed additions.

## 7.4 GSAC

Since 1997, the NCEDC has collaborated with UN-AVCO and other members of the GPS community on the development of the GPS Seamless Archive Centers (GSAC) project. When completed, this project will allow a user to access the most current version of GPS data and metadata from distributed archive locations. The NCEDC is participating at several levels in the GSAC project: as a primary provider of data collected from core BARD stations and USGS MP surveys, as a wholesale collection point for other data collected in northern California, and as a retail provider for the global distribution of all data archived within the GSAC system. We have helped to define database schema and file formats for the GSAC project, and for several years have produced complete and incremental monumentation and data holdings files describing the data sets that are produced by the BARD project or archived at the NCEDC so that other members of the GSAC community can provide up-to-date information about our holdings. Currently, the NCEDC is the primary provider for over 74,000 data files from over 1400 continuous and survey-mode monuments. The data holdings records for these data have been incorporated into a preliminary version of the retailer system currently undergoing testing, which should become publicly available in late 2002.

## 7.5 Web Pages

The NCEDC developed its Web pages in the early days of the Web. Unfortunately, time constraints have kept the pages somewhat static and limited in their use. In June of 2002, the NCEDC began an project to update and expand their Web offerings. This project is still underway and should be completed in the fall of 2002.

## 8. Acknowledgements

# Chapter 14

# Outreach and Educational Activities

## 1.  Introduction

The BSL is involved in a variety of outreach activities, ranging from lectures and lab tours to educational displays and the development of classroom materials for K-12 teachers. We maintain an earthquake information tape (510-642-2160) and an extensive set of Web pages, providing basic earthquake and seismic hazard information for northern and central California.

## 2.  Outreach Overview

The BSL has several on-going outreach programs, such as the educational displays, WWW development, and the Earthquake Research Affiliates Program.

### 2.1  Educational Displays

As part of the BSL's outreach activities, we have made REDI earthquake data available to a number of universities, colleges, and museums as educational displays. As noted above, this year marked the expansion of this program to the K-12 environment. Participating organizations receive a REDI pager and the Qpager software to display the earthquake information. The Qpager program maps the previous seven days of seismicity, with earthquake shown as a dot. The size of the dot indicates the magnitude of the event, while the color of the dot indicates its age. These educational displays have been installed at UC Berkeley (McCone Hall, Earthquake Engineering Research Center, LHS), California Academy of Sciences, CSU Fresno, CSU Northridge, CSU Sacramento, Caltech, College of the Redwoods, Fresno City College, Humboldt State University, San Diego State University, Sonoma State University, Stanford University (Blume Engineering Center, Department of Geophysics), UC Davis, UC Santa Cruz, UC San Diego, and USC. In a pilot project initiated two years ago, the San Francisco Unified School Dis trict has been given two pager systems for use in middle school classrooms.

In addition to the seismicity displays, the BSL provides local waveform feeds for helicorders at several visitor centers associated with BDSN stations (CMB and MHC). Organizations such as LHS, KRON, and KPIX receive feeds from BKS via dedicated phone lines for display, while the USGS Menlo Park uses data from CMB for display in the lobby of the seismology building. The BSL has also loaned a seismometer and helicorder display to the San Leandro Unified School District for their use in science classes.

### 2.2  WWW

Over the last year, we have continued to expand our presence on the WWW. Our primary goal has been to provide a source of earthquake information for the public, although we also provide information about the networks, such as station profiles, which benefits the research community as well. We provide such information as seminar schedules, course advertisements, descriptions of operations and research, updates on recent earthquake activity, details on Bay Area seismicity and hazards, and links to other earthquake and earth science servers. We also use the WWW server for our own information distribution, with such details as the computing and operational resources, rosters, and schedules for various purposes.

### 2.3  Earthquake Research Affiliates Program

The UC Berkeley Earthquake Research Affiliates (ERA) Program is an outreach project of the BSL, the Department of Geology and Geophysics, and the Earthquake Engineering Research Center. The purpose is to promote the support of earthquake research while involving corporations and governmental agencies in academic investigation and education activities such as conferences and field trips. The ERA program provides an interface between the academic investigation and practical application of earthquake studies.

## 3.  2000-2001 Activities

### 3.1  Interactive University Project

During 2001-2002, the ISTAT (Integrating Science, Teaching, and Technology) Project drew to a close.

This collaboration, part of the the Interactive University Project (IUP), brought the BSL, the Museum of Paleontology, the Space Sciences Laboratory, and the Center for Particle Astrophysics together in an earth and space science cluster, with a focus on education in "Integrating Science, Teaching, and Technology" (ISTAT) with a focus grades 6-12. We received a small 18 month grant in 1996 to initiate this project. Based on our success, we submitted a second proposal in 1998 and received funding for a 3 year project with Gloria Davis Middle School, Horace Mann Academic Middle School, Galileo High School, Mission High School, and Thurgood Marshall Academic High School in the San Francisco Unified School District (`http://www.UCMP.Berkeley.EDU/IU/`).

During this project, we worked with lead teachers to review the new San Francisco science and math standards and to identify "gaps" between existing resources and materials and the required content. San Francisco has recently adopted new textbooks with the goal of teaching Earth and Space Sciences in the 9th grade. We worked with the teachers to develop a working outline for the curriculum and to supplement the text with activities and resources.

The draft Earth science curriculum now includes a scope and sequence, course outlines for 6, 9, and 12 week modules, and preliminary assessment materials and is available on the Web at `http://seismo.berkeley.edu/seismo/istat/9th/`.

## 3.2  Teachers' Workshop

In the fall of 2001, Dr. Gee joined scientists from UCMP, San Francisco State University, San Jose State University, and the Cal Academy of Sciences to design an earth science course for middle school teachers. The course was composed of 5 workshops and Dr. Gee presented material on earthquakes.

## 3.3  Tours and Presentations

BSL staff have also spent considerable time with public relations activities during the past year. Several tours are given each month, with audiences ranging from middle-school students to scientists and engineers from China and Japan. This year, we saw a sizeable increase in visits from "home-school" students.

The BSL hosted several special groups during 2001-2002. A number of educational groups visited, including a class from Mills College a groupd of California city managers attending a conference sponsored by the Goldman School of Public Policy.

In addition to the tours, Drs. Romanowicz, Dreger, Uhrhammer, and Gee presented talks on earthquakes and related phenomena to public groups. Dr. Gee gave a presentation for the City of Berkeley, directed at the volunteers participating in the Disaster Resistent Berkeley program.

## 3.4  Take Your Child to Work Day

The BSL was unable to participate in Cal Day this year, due to a scheduling conflict with the annual meeting of the Seismological Society of America. The BSL did participate in "Take Your Child to Work Day" and hosted many UC Berkeley parents and their children. The visitors learned about UC Berkeley's role in earthquake monitoring, found out how many earthquakes occurred on their birthday, played with an "earthquake machine", made P and S-waves, learned about earthquake preparedness, and were given sample seismograms.

## 3.5  Workshops

The BSL co-hosted a workshop with Jack Boatwright of the USGS to discuss coordination of seismic instrumentation in Northern California, the generation and distribution of ShakeMaps, and the evolution of ANSS in March 2002. The workshop included representatives from the BSL, the USGS Menlo Park, the California Geological Survey, the California Office of Emergency Services, and PG&E.

## 3.6  1906 Centennial

In less than 4 years, the Bay Area will celebrate the centennial of the 1906 earthquake. In June, 2002, the BSL hosted a meeting of representatives from the USGS and the Seismological Society of America (SSA) to begin planning for this historic anniversary. The BSL and the USGS have agreed to co-host the 2006 Annual Meeting of the SSA and discussed several ideas for organizing the meeting with Executive Director Susan Newman. In addition to plans for the scientific meeting, the BSL is collaborating with other campus units on commemorative activities.

# 4.  Acknowledgements