Chapter 3

Broadening Engagement

Berkeley Seismo Lab @BerkeleySeismo 5 Aug

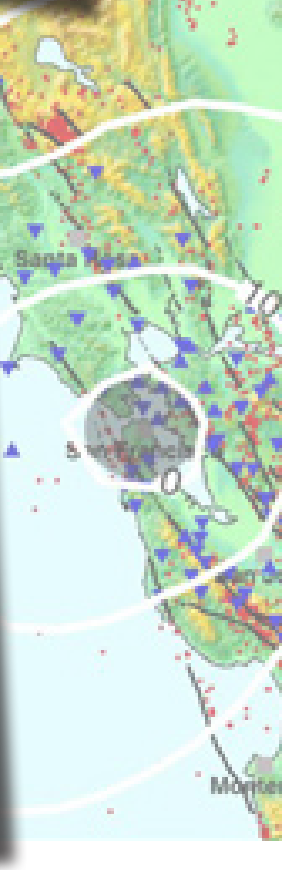
BSL's own Peggy Hellweg explains the powerful quake in China on CCTV: youtu.be/aZpQfLxThtM via @YouTube

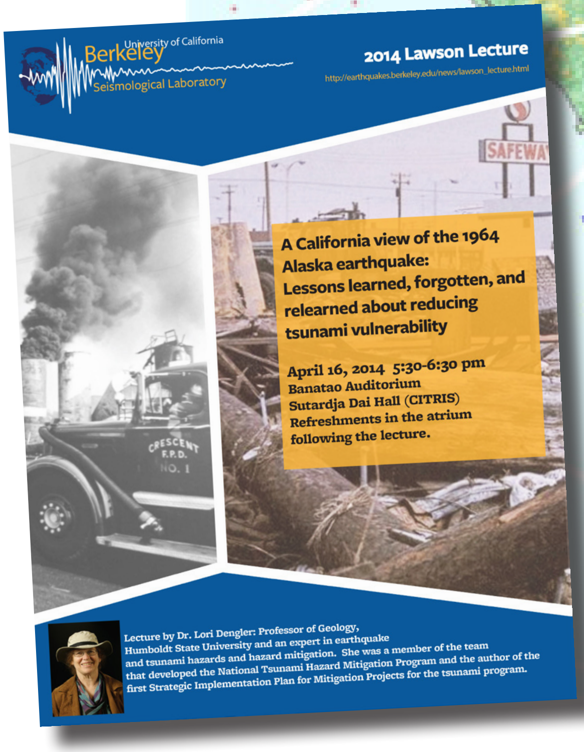
Berkeley Seismo Lab @BerkeleySeismo 24 Jul

Film crews on set in San Francisco for an earthquake catastrophe film: San Andreas. sfgate.com/bayarea/articl…

Berkeley Seismo Lab @BerkeleySeismo 21 Jul

Was your state tagged as a high earthquake risk zone? The new hazard maps from USGS are now available. on.natgeo.com/1jCjbNd via @NatGeo





2014 Lawson Lecture

http://earthquakes.berkeley.edu/news/lawson_lecture.html

A California view of the 1964 Alaska earthquake: Lessons learned, forgotten, and relearned about reducing tsunami vulnerability

April 16, 2014 5:30-6:30 pm
Banatao Auditorium
Sutardja Dai Hall (CITRIS)
Refreshments in the atrium following the lecture.

Lecture by Dr. Lori Dengler: Professor of Geology, Humboldt State University and an expert in earthquake and tsunami hazards and hazard mitigation. She was a member of the team that developed the National Tsunami Hazard Mitigation Program and the author of the first Strategic Implementation Plan for Mitigation Projects for the tsunami program.

1 Earthquake Research Affiliates Program

Introduction

The Earthquake Research Affiliates (ERA) program at the Berkeley Seismological Laboratory (BSL) promotes the support of seismological research through industrial and governmental involvement. The affiliates program produces a newsletter, provides a mechanism to link industry and public sector groups with interests in BSL research, and provides an opportunity for resiliency organizations to interface with earthquake science.

Earthquake Research Affiliates Program

The BSL draws on the diversity of the interdisciplinary earthquake and solid earth research community at UC Berkeley. Augmenting these efforts, the ERA program provides a forum for the exchange of ideas and information between industry and public sector organizations with an interest in BSL research and the scientists themselves. The mission of the ERA program is to inspire, nurture, and sustain vibrant public-private and industrial-academic partnerships focused on the development and use of innovative earthquake information products, including alert services, and other novel seismological measurement technologies. The program is designed to promote the application of new research results and technology, and to provide a forum for inviting optimal and essential users to participate in the development and testing of new technologies, with the goal of introducing them into the marketplace. Current ERA members include the Bay Area Rapid Transit District (BART), the University of California, Berkeley Police Department, (UCBPD), the San Francisco Department of Emergency Management (SFDEM), and Google.

Regular interaction with each group is a key aspect of the program. Recently, we have expanded our engagement with the SFDEM to include SF Fire, Police, 311, 911, SFO Airport, the Real Estate division, Public Works, and the MTA. This expansion allows us to begin to work toward uses and automated controls for earthquake early warning messages on a city-wide scale. Monthly meetings with our counterparts at Caltech and the University of Washington are supporting this endeavor.

Senate Bill SB135 Signed into Law

A California bill calling for the creation of a public earthquake early warning (EEW) system for the state was put forward by State Senator Alex Padilla (D-District 20) and unanimously passed both the Senate and the Assembly. In September of 2013, Governor Jerry Brown signed the bill into law, which tasks the California Governor's Office of Emergency Services (CalOES) with defining funding sources to support the build-out and operations costs for the project.

The Berkeley Seismological Laboratory, and in particular Director Richard Allen, have been intimately involved in providing support and scientific expertise for this endeavor. Dr. Allen and Dr. Jennifer Strauss made several trips to the State and Federal Capitol to inform and update legislators on the Shake Alert system, and Dr. Allen has provided testimony at key points during the bill's progress.

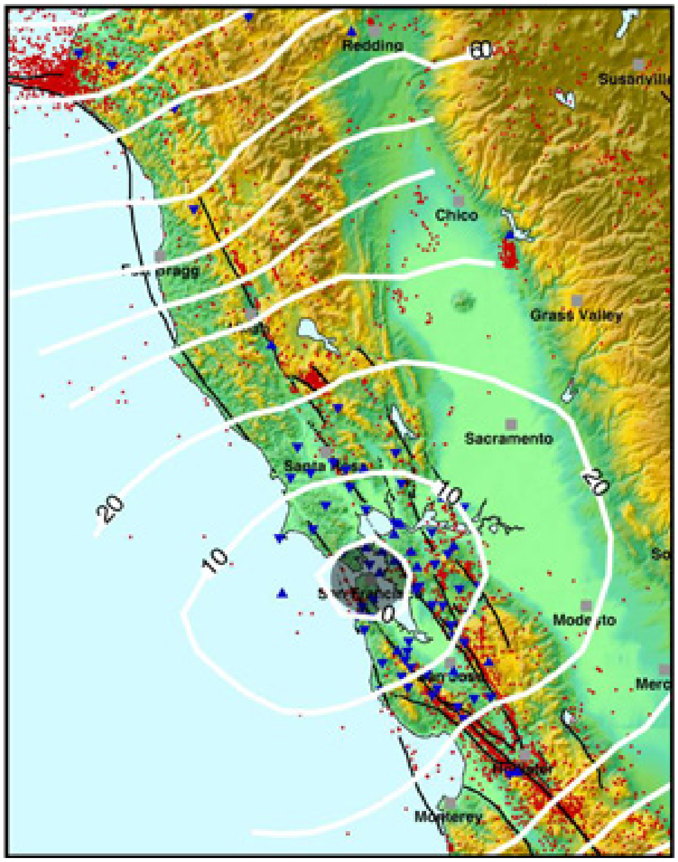


Figure 3.1.1: The lines on this map show warning times for San Francisco for major earthquakes at various locations, which are quickly detected by an early warning system. The gray area marks the "blind zone." There will be no warning for earthquakes in this area.

CalOES Working Groups

Dr. Allen, Dr. Strauss, and Dr. Hellweg were part of CalOES' California Earthquake Early Warning System (CEEWS) working group. This group drafted the charter, discussed stakeholder roles and responsibilities, and crafted a proposal to establish committees and address charter objectives. The CEEWS charter was approved in early 2014, and in May the kickoff meetings to brief interested working group parties were held in Northern and Southern California.

CalOES is now moving forward with an implementation plan to create the system by establishing committees of subject matter experts. The BSL is involved in the Management, Model, Standards, Steering, and Education and Training committees for the CEEWS. Of most interest to the ERA members is the Education and Training committee. Dr. Strauss is interfacing with ShakeAlert beta testers (see 2013 BSL Annual Report section 3.1) and the rest of the committee to ensure that active users have a platform to share their experience with the system. The experience of beta users such as the SFDEM (see below) will be crucial as it gives a real world outlook and solutions moving forward.

San Francisco EEW Group

This year the San Francisco ERA participants have significantly increased their interaction with the earthquake early warning system beta test. Over a period of six months, various city agencies including those dealing with fire, police, hospitals, and airports have come together for monthly meetings, coordinated by Dr. Strauss, to learn about the ShakeAlert system and start developing their own procedures for earthquake alert response.

The various agencies have installed the UserDisplay and are drafting response action matrices applicable to their particular needs. The agencies are coming together to determine which needs are common amongst all agencies, and which are agency specific. The goal is that the commonalties can all be addressed under one umbrella. Now that the initial meetings have concluded, the agencies are fleshing out what will be required to meet all of their desired automated actions and controls. This is an important step, because some actions and controls might be quick and inexpensive to implement, whereas others might require new funding requests, policy changes, or collaborations that need to be looked into.

100 Resilient Cities

The City of San Francisco, along with Alameda, Berkeley, and Oakland, was selected for the first round of the Rockefeller Foundation Centennial challenge of 100 Resilient Cities. The 100 Resilient Cities offers a unique opportunity to have a regional conversation about shared resilience risks and opportunities. As a 100 Resilient Cities member, the four Bay Area cities have a great opportunity to strengthen their resilience commitment via:

1. Grant funds to hire a Chief Resilience Officer (CRO) who will lead the development and implementation of the City's resilience strategy.
2. Technical support in the development of the City's resilience strategy.
3. Membership in the global 100 Resilient Cities network.
4. Access to a platform of resilience-building tools.

The ERA program interaction with resiliency agencies around the Bay Area prompted Dr. Strauss to receive an invitation from San Francisco's Mayor Lee to participate in the Agenda Setting Workshop March 17–18, 2014. There, she was able to present the ShakeAlert project to other resiliency groups and the ERA members who are helping to drive the effort.

3rd International Conference on EEW

The BSL is organizing the 3rd International Conference on EEW for September, 2014. This three-day meeting will facilitate implementation of earthquake alerts. The event will bring together scientists, policy makers, engineers, social scientists, and business representatives from public and private sector institutions to examine the state of the art in earthquake early warning today and to innovate new ways to push the technology forward. Channeling the experience of these interdisciplinary groups, the meeting will address current challenges, lessons learned from systems currently in operation worldwide, and ultimately forge a path toward fulfillment of public early warning systems in the U.S. and around the world.

ERA members will play a crucial role in this meeting. Unlike the previous two international meetings (held at Caltech and Kyoto University), the aim of this conference is to provide the perspectives of the end user with a more prominent role. ERA members will be able to engage other industry groups from around the world, and get a taste of best practices for automated controls, alert mechanisms, and general hazard mitigation involving early warning.

Continuing Engagement

The ERA program continues to seek out new avenues to foster continuing engagement between seismologists and outside industry and government groups. Dr. Strauss spoke at the Business Recovery Managers Association's July 2013 Membership Meeting in Oakland, CA on July 25, 2013 about shaping response and recovery with Earthquake Early Warning. She gave a similar presentation to the California Emergency Services Association's Annual Training Conference in Santa Rosa, CA on October 16, 2013. She also spoke directly to city resiliency leaders at the San Francisco Planning and Urban Research Association Lunchtime Forum later that same month.

Interactions with other groups, including the San Francisco Office of Earthquake Safety, the Lifelines Council, and the Community Action for Seismic Safety groups, is ongoing.

Acknowledgements

Jennifer Strauss heads the Earthquake Research Affiliates program with oversight by Richard Allen and Peggy Hellweg. Jennifer Strauss and Peggy Hellweg contributed to the preparation of this section.

2 Engaging the Public

Introduction

One of the core missions of the Berkeley Seismological Laboratory is to enable the broad consumption of earthquake information and solid earth science through education and outreach to all sectors of society. While many of our outreach and education activities focus on lectures, tours, and public events, we also engage the public through collaborative initiatives and products. Highlights from this year include contributions to Bloom, MyQuake, and Science on a Sphere.

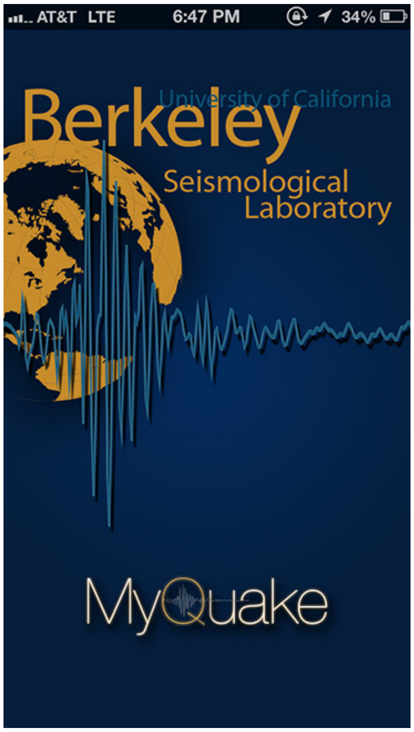


Figure 3.2.2: Opening screen for the BSL's new iPhone app: MyQuake.

MyQuake

The MyQuake app (released in July 2013) is the product of an undergraduate student research project in collaboration with the BSL. Rohan Agarwal (computer science) and Cora Bernard (geophysics) developed the app.

MyQuake maps earthquakes that occurred recently in the California region and across the globe. It also provides information about large damaging historic earthquakes in California, and calculates the shaking intensity at user-defined locations for both the historic and current earthquakes. For example, it calculates that at Berkeley, the shaking for the 1868 Hayward earthquake was Intensity VII, while for the 1906 Great San Francisco earthquake it was Intensity VIII. The app then links to videos that show what it is like to experience shaking of that intensity.

MyQuake is completely ad-free and provides a smooth, intuitive user interface to facilitate learning about earthquakes, keeping the user informed and preparing them for the next big earthquake.

MyQuake is available for free at the iTunes store. Since launching, the app has been downloaded approximately 8000 times and users are accessing the USGS recent earthquake pages around 50 times on a given day. They are also accessing the earthquake history and the tips pages. This means that users are actually using the app and learning more about earthquakes and earthquake preparedness.

Science on a Sphere

In partnership with the Lawrence Hall of Science (LHS), the lab is developing earthquake-related content for joint display on a flat screen, together with NOAA's Science on a Sphere (SOS, http://sos.noaa.gov/What_is_SOS/). The goal of SOS is to amass display products and project them on a six-foot diameter sphere to foster education and discovery in the realm of environmental processes. The final products from boith institutions will be made available to both the Science on a Sphere members and to the IRIS Active Earth Display Kiosk (IAEDK) network (see http://www.iris.edu/hq/programs/education_and_outreach/museum_displays/active_earth). The BSL is tasked with content and scientific accuracy for this project, while the LHS is in charge of technical aspects and evaluation of pedagogical content.

The BSL's contributions consist of two main themes: "Seismic Waves" and "Disasters". This year, Jennifer Taggart, Clay Miller, and William Hawley have assembled content, media, and graphics for inclusion on the IAEDK slides and popups, with a focus on three earthquake-related disasters: Liquefaction, Tsunamis, and Building Collapse. The Tsunami slides explain tsunami generation and discuss the 2011 Tohoku and 2004 Sumatra tsunamis. Building collapse compares and contrasts the 2010 Haiti disaster with the low level of shaking damage in Sendai after the much larger Tohoku earthquake. Finally, the liquefaction slides explain what liquefaction is and give examples of how it can be dangerous (infrastructure damage during the 2011 Christchurch earthquake, landslides in the 2008 Wenchuan earthquake, buildings tilting and then toppling over in a 1964 Japan quake, San Francisco Marina district damage after the 1989 Loma Prieta quake).

We exhibited a scale model of the project at the American Geophysical Union (AGU) fall meeting in San Francisco in December 2013 to gather feedback about the user experience as well as the science presented.

After implementation of the feedback we received, we started drafting content for additional content. Jennifer Taggart and Clay Miller added content about seismic waves and William Hawley added content describing how seismic waves can be used to image the interior of the earth. These topics allow the

Fundamental Research: Learn more about how the BSL is bringing Earthquake Early Warning to the state of California, the makeup of Earth's upper mantle, and what is actually happening deep inside the San Andreas Fault.

Hazard Information: Berkeley operates several different networks and observatories in California. How is data from the BSL used to mitigate or even prevent disasters? How does Berkeley contribute to earthquake understanding and awareness? Exploring data products produced by the BSL can answer these questions and more.

Broad Education: Explore our outreach website to find a virtual tour of the Hayward Fault, learn how to prepare for an earthquake, and track seismic waves as they travel through the earth!

These are the three key aspects of BSL's mission

Sounding the Alarm: An early warning system would save thousands of lives when the next major earthquake hits. But will California find the money to implement it? - East Bay Express

Download the new FREE App developed by the BSL for information on earthquakes nearby! Also learn about historic earthquakes where you live. Check it out!

Seismo Blog: Superstorm Sandy Wiggled the Whole Continent

As their name suggests, seismometers are there to measure earthquakes. After all "seismos" is the ancient Greek word for quake and the word "meter" derives from another Greek verb for measuring. In reality, however, the name "seismometer" is quite a misnomer for these marvels of electromechanical engineering...

Berkeley Seismological Lab
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Figure 3.2.3: The redesigned homepage of the Berekeley Seismological Lab. Notice the real-time earthquake map that organizes earthquakes by date and magnitude.

BSL to present a little more scientific content than was involved with the previous themes. In addition, the BSL contacted Alan Jones, from Binghamton University in New York, who has written various graphical displays of seismic waves. With feedback from the BSL and the LHS, he modified existing codes to create several beautiful animations that can be displayed on the sphere. The animations made in this process will become part of NOAA's public SOS database, usable by anyone in the world.

BSL Website

This academic year, the BSL's web pages went through several phases of modernization. The most prominent change is the real-time earthquake map on our homepage. Visitors to the homepage are now greeted with a dynamic map showing all earthquakes detected in California. Earthquakes appear in real time as squares, colored by age in days and sized by magnitude in order to give the most emphasis to the earthquakes likely to be felt widely. Each individual square can be clicked on, initiating a popup balloon containing the event's magnitude, date and time, depth, and distance to the nearest town, as well as links to ShakeMaps and other earthquake information products. Users can zoom and pan to explore earthquakes around the world as well as in particular regions like The Geysers, CA. When an earthquake above magnitude 3.5 occurs in the state's reporting area, the default map zooms to that earthquake and stays there for 48 hours (or until a larger earthquake happens). A manual override allows BSL seismologists to hold the map's focus at a particular point, should one or more events of particular interest occur.

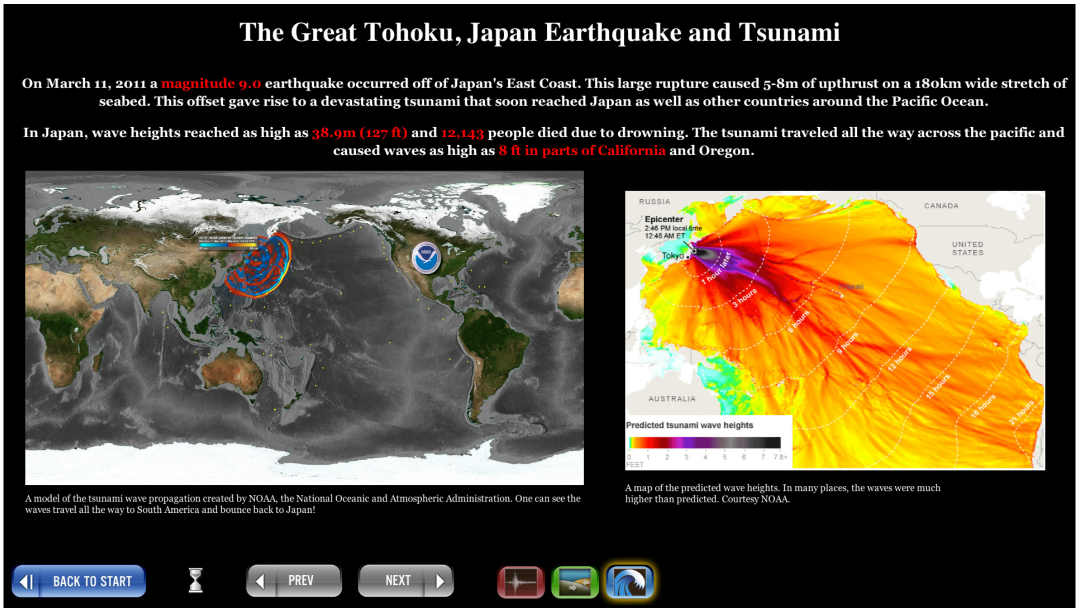
In addition to the real-time earthquake map, the homepage is complemented by a slideshow and clickable carousel created from the popular jQuery plugin, bxSlider. Our navigation menu has been improved to funnel visitors toward the pages most relevant to them. Visitors now hover over a menu item describing who they are, such as "For Researchers," which triggers a two-column dropdown menu containing an organized list of pages targeted toward their interests. Last but not least, the BSL webpages are now served up as http://earthquakes.berkeley.edu as well as our old URL, http://seismo.berkeley.edu.

The BSL continues to educate and inform the public through our webpages, providing a seismology blog (http://seismo.berkeley.edu/blog), videos, an earthquake FAQ, and resources for teachers and those who wish to dig deeper. Our "seismic networks" web pages also serve the research community, providing detailed information about each of our seismic stations.

Social Media

The BSL has long been committed to public outreach, and in this digital age, we have expanded the ways in which we can share information with the public by creating a Twitter profile as well as a YouTube page.

The BSL created the twitter account with the handle of @BerkeleySeismo to send interesting and timely tweets out to a broad, global audience. Twitter is a fantastic platform for the BSL to reach a wide audience due to its prevalence and popularity, as well as its functionality as a *de facto* news aggregator. We send tweets on a regular basis that feature exciting new research, public safety, seismic history, the BSL's Seismo Blog, BSL events or other seismic information. The BSL has gained 237 followers in a short amount of time with more following us all the time.



The Great Tohoku, Japan Earthquake and Tsunami

On March 11, 2011 a magnitude 9.0 earthquake occurred off of Japan's East Coast. This large rupture caused 5-8m of upthrust on a 180km wide stretch of seabed. This offset gave rise to a devastating tsunami that soon reached Japan as well as other countries around the Pacific Ocean.

In Japan, wave heights reached as high as 38.9m (127 ft) and 12,143 people died due to drowning. The tsunami traveled all the way across the pacific and caused waves as high as 8 ft in parts of California and Oregon.

A model of the tsunami wave propagation created by NOAA, the National Oceanic and Atmospheric Administration. One can see the waves travel all the way to South America and bounce back to Japan!

A map of the predicted wave heights. In many places, the waves were much higher than predicted. Courtesy NOAA.

Figure 3.2.4: One of the slides of the IRIS AED the BSL has customized and displayed in McCone Hall. This slide has an animation of wave propagation from the tsunami caused by the *M*9.0 Tohoku earthquake. The image to the right shows predicted wave heights of the tsunami.

Follow us for BSL updates!

Another Social Media outlet the BSL has utilized in the past year to reach a broader, more global audience is YouTube. The BSL has many great videos for the public, and we are constantly creatng more. YouTube was an obvoius outlet to showcase these videos. We have put up several videos of past Lawson Lectures, as well as several other informative and engaging videos, most notably the well made series on a recent scientific cruise that took place in the summer of 2014. Our YouTube page can be found at https://www.youtube.com/user/BerkeleySeismoLab.

The BSL webpages now feature icon links in the top right for Twitter, YouTube, and RSS Feed easy access.

Media

This year, the BSL continued its outreach to the public by providing numerous and varied media sources with interviews and information. The bulk of media requests we get are for newspaper and other print sources; however, we also gave interviews to KQED, a public radio station, as well as to MBC, a Korean broadcasting company. This year was particularly important and busy for media inquiries due to the pronounced status of our Earthquake Early Warning efforts. There were several major events that caused particular interest, including a recent cooperation with Bay Area Rapid Transit (BART) and the announcement of California Senate Bill 135 (see Broadening Engagement Section 1).

DOIs

The BSL has made a much more dedicated effort in the past few years to keep track of metrics about data usage at the lab. It is important for us to know who is using our data and how often it is being used, both in terms of how much data are downloaded from the NCEDC (see Operations Section 4.8) and how often data the BSL collects is used in scholarly journals. The latter part of this goal was especially difficult to discern due to a lack of consistency with how authors cite the BSL/NCEDC. In order to fix this problem, the BSL has created DOIs (digital object identifiers) for various data realms one might use in research. A DOI is a commonly used identifier that refers to a specific and unique data set. We have created four DOIs—one for the NCEDC, BK seismic network, BP network, and BARD network. In addition to the DOI, there are metadata associated with each DOI where we can detail such information as contributing organizations and institutions, the archive date range, and the relationship between the four DOIs. We chose to create custom DOIs for ease of use. The four DOIs are: DOI:10.7932/BDSN, DOI:10.7932/HRSN, DOI:10.7932/NCEDC, DOI:10.7932/BARD for the BK network, the BP network, the NCEDC and the BARD network respectively.

The most important part of the DOI, however, is that it is pithy and we can greatly reduce our citation length. For each of the four DOIs, we have rewritten our citation statement to make it simpler and shorter, as well as made it more visible on the NCEDC website.

Displays

In addition to the more modern look of the BSL's web pages, we have also added several engaging displays throughout our building (McCone Hall) to encourage public education, awareness, and fascination.

In the first floor lobby we have showcased an interactive display that allows visitors to explore current earthquakes and learn about the science of earthquakes. The display was created using an IRIS web-based Active Earth Display (AED) template. The template allows the BSL to create up to 25 unique slides with completely customized content that users can cycle through using a touch pad. The 25 slides are broken into three categories and users can click on the category they want to view. When the display has been inactive for five minutes, it reloads the home slide, which is a real-time seismogram of the last three days of data from station BKS.BK, located on the UC Berkeley campus. The display is shown on a large monitor, and it has been optimized for our specific setup. However, it is web-based, so it can be accessed anywhere. If one wishes to view the display, he or she can go to http://www.iris.edu/aed2/index.phtml?code=BSL2012.

On the 2nd floor of McCone Hall, with the same setup as in the 1st floor lobby, we have a looping Google Earth tour fly-through. The tour shows viewers faults and historic earthquakes in California and takes them to the sites of a few of our stations, including an underwater site. It does all this by seamlessly "flying" from place to place, taking advantage of Google's visually stunning databases of topography and city data.

In addition to this Google Earth fly-through, this year we have updated the wall on which the monitor is stationed. Thanks to Jennifer Strauss, we have a beautiful display of historic and informative photos and text concerning Bay Area seismicity, including images from the Loma Prieta, 1906, and 1868 earthquakes.

In the BSL conference room, we have three different displays running on four monitors. On one of the monitors is a seismogram from the last four days of data from station BKS.BK, a seismic station located on UC Berkeley's campus. The data is displayed through the SWARM program. We also use the SWARM program to create a vibrant map of California, overlaid with the location of our BK network of seismic stations. We have enabled a few of these stations to show the last 10 minutes of data in real time. With these seismograms displayed throughout the state, one can see seismic activity throughout California in real time.

On our last monitor, we alternate between two programs. The first and most common is *seisnetwatch,* and the other is the California Integrated Seismic Network (CISN) User Display. *Seisnetwatch* is a tool the BSL uses to monitor station quality and health. It allows us to see the stations of the Berkeley Digital Seismic Network (BDSN) and their health for the past month. The CISN User Display is part of an effort at the BSL to create a Earthquake Early Warning System (EEWS) (see Broadening Engagment Section 1). The display will issue an alert of an earthquake before strong shaking is felt at our location (provided the epicenter is not too close).

Acknowledgements

Peggy Hellweg oversees the Public Engagement projects at the BSL. Stephane Zuzlewski created the earthquake map for the BSL homepage. Our seismology blog is written by Horst Rademacher.

Special acknowledgements to our external collaborators: Ken Goldberg, Rohan Agarwal, and Cora Bernard, Toshi Komatsu and Gretchen Walker at LHS. Jennifer Taggart, Clay Miller, Peggy Hellweg, and Jennifer Strauss contributed to the to the preparation of this section.

3 Science and Society

Introduction

BSL faculty, staff, and graduate students are involved in a wide variety of outreach activities, ranging from public lectures to tours of the Hayward Fault geomorphology on campus. This year, we continued our involvement in CalDay and other traditional activities, and also helped a few teams competing for the First Lego League.

Lawson Lecture

The Lawson Lecture is a free, public lecture hosted by the BSL each year around the anniversary of the 1906 San Francisco earthquake. This year, on April 16, 2014, Dr. Lori Dengler gave listeners "A California view of the 1964 Alaska earthquake: lessons learned, forgotten, and relearned about reducing tsunami vulnerability". The lecture was held in the Banatao Auditorium of Sutardja Dai Hall on campus and for the second year, was followed by a light reception.

Prof. Dengler is an expert in earthquake and tsunami hazards and hazard mitigation. She was a member of the team that developed the National Tsunami Hazard Mitigation Program and the author of the first Strategic Implementation Plan for Mitigation Projects for the tsunami program. Prof. Dengler guided those present on a tour of the tsunami program, then versus now.

Her talk described how, at the time of the 1964 Great Alaska Earthquake, U.S. tsunami hazard was considered a Hawaiian problem. On March 27, 1964, it took over three hours for a tsunami alert bulletin to reach California. Crescent City—California's northernmost coastal city—did not begin notifying vulnerable residents until a half hour before surges arrived. In Crescent City, the tsunami killed ten, flooded 29 blocks, damaged or destroyed nearly 100 structures and led to permanently altering the downtown area. The tsunami also caused damage in other California coastal areas, killing a person in Bodega Bay and Los Angeles, destroying boats and docks in San Francisco Bay and wreaking havoc on many areas of the coast. This talk recounted the events of 1964 from a California and Crescent City perspective, traced mitigation measures taken after the tsunami, and examined how California's tsunami hazard and tsunami mitigation efforts have changed in the past five decades.

The Lawson Lectures are viewable as a Flash video at http://earthquakes.berkeley.edu/news/lawson_lecture.html.

First Lego League

Members of the BSL were interviewed by several teams during the First Lego League 2013 Nature's Fury Challenge. The First Lego League is a robotics competition for 9–16 year olds. This year, the theme was Nature's Fury. Teams programmed an autonomous Lego Mindstorms robot to score points on a playing field reflecting various natural disaster scenarios. They also had to identify a natural disaster problem and develop a solution to it.

Figure 3.3.1: From top left clockwise: The Tornado of Ideas and their team captain with their ticket to the state competition, Jennifer Strauss and Michael Faggetter with the Rovers, and Ronni Grapenthin with the Robo Maniacs team.

Beginning in October of 2013, several Lego League groups began contacting the BSL to request interviews from the scientists about earthquake hazards (see Figure 3.3.1). They learned the basics of earthquakes, how shaking can impact buildings and people, and how we measure the earthquake's severity. They also got feedback and asked advice about their team's solution to their chosen natural disaster problem.

A subset of the teams we helped kept in touch and sent us updates on their progress through the competition. The Robo Maniacs team of 5th and 6th graders came in 1st place in the first level qualifier. The Tornado of Ideas group qualified for the state competition in South Carolina and received a Core Values award. We held those interviews over Skype, since they could not take a field trip to California to speak with the BSL in person. The youngest group, the Rovers, were only 8 and 9 years old, but were so hooked on the competition that they are prepared to compete again next year.

CalDay—BSL Open House

The weekend before the Lawson Lecture, the Seismo Lab participated in UC Berkeley's open house for prospective students and general day of fun for community members: CalDay. Many departments have exhibits and demonstrations for everyone and every interest. The Berkeley Seismological Lab is proud to share in this tradition. Visitors learned about earthquakes, plate tectonics, tsunamis and more. Younger guests got to jump up and down to create their own earthquake and received a seismogram of the output. They also explored seismic waves using giant springs and received a stamp in the Science@Cal passport. All guests watched BSL seismic data in real time through the SWARM application running in the conference room.

CalDay ran from 10:00 AM–3:00 PM on Saturday April 12, 2014.

Tours

During 2013–2014, many groups, ranging from middle-school students to international guests, visited the BSL for talks, tours, and hands-on science experiences.

For most of this fiscal year, the tours involved groups from the First Lego League, mentioned above. In October, Jennifer Strauss and Qingkai Kong gave a laboratory tour and discussed Earthquake Early Warning with researchers from Beijing.

On February 6th, Larry Hayne's Richmond-area 2nd grade class visited the Seismo Lab. About 25 children, plus their adult chaperones had a hands-on introduction to seismology. Ronnie Grapenthin, Jennifer Strauss, Clay Miller, and Jennifer Taggart ran "stations" with springs, a stick-slip hand crank, and netquakes activities followed by a question and answer session.

Ongoing Activities

As in previous years, the members of the BSL gave several external lectures.

Jennifer Strauss presented about earthquake early warning at East Bay MUD in Oakland for the BRMA (Business Recovery Managers Association) July meeting. On September 26th, Peggy Hellweg spoke at Point Reyes Bear Valley Visitor Center, about "Earthquakes in your Backyard." Jennifer Strauss spoke at the CESA annual meeting on October 17th in Santa Rosa: "Shaping Response and Recovery with EEW". On October 9th, Peggy Hellweg spoke at Gateway Science Museum in Chico with a reprise of the "Earthquakes in our Backyard" lecture.

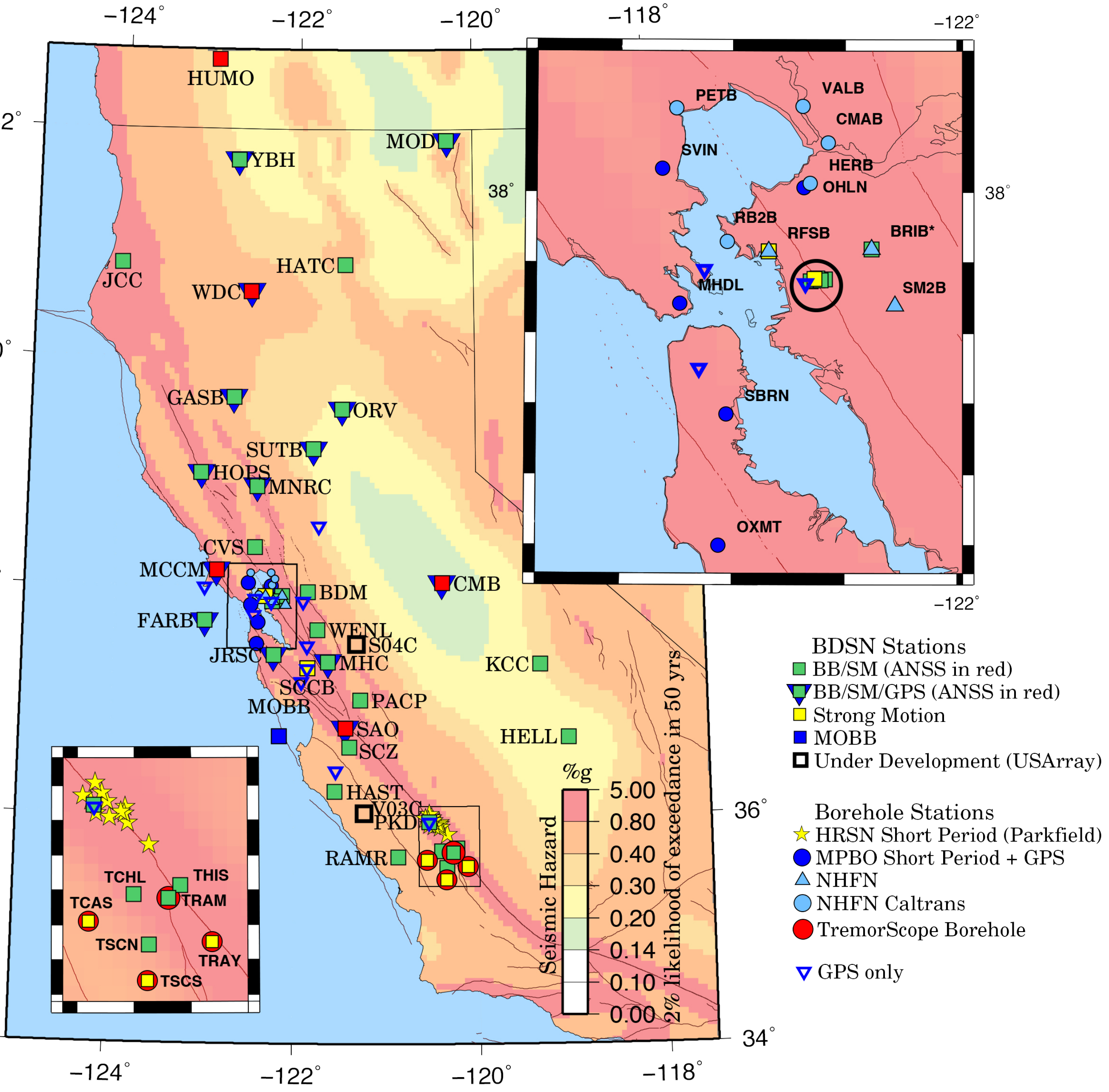
The BSL also hosted a delegation from the Beijing Earthquake Administration, who were here to talk with our graduate students and scientists. Richard Allen gave them updates about earthquake early warning and our state-of-the-art seismology network.

Acknowledgements

Peggy Hellweg oversees the outreach activities at the BSL. Richard Allen, Qingkai Kong, Ronni Grapenthin, Jennifer Taggart, Clayton Miller, Jennifer Strauss, and many other faculty, staff, and students at the BSL contribute to the outreach activities. Peggy Hellweg, Clayton Miller, and Jennifer Strauss contributed to the preparation of this section.

Chapter 4

Operations



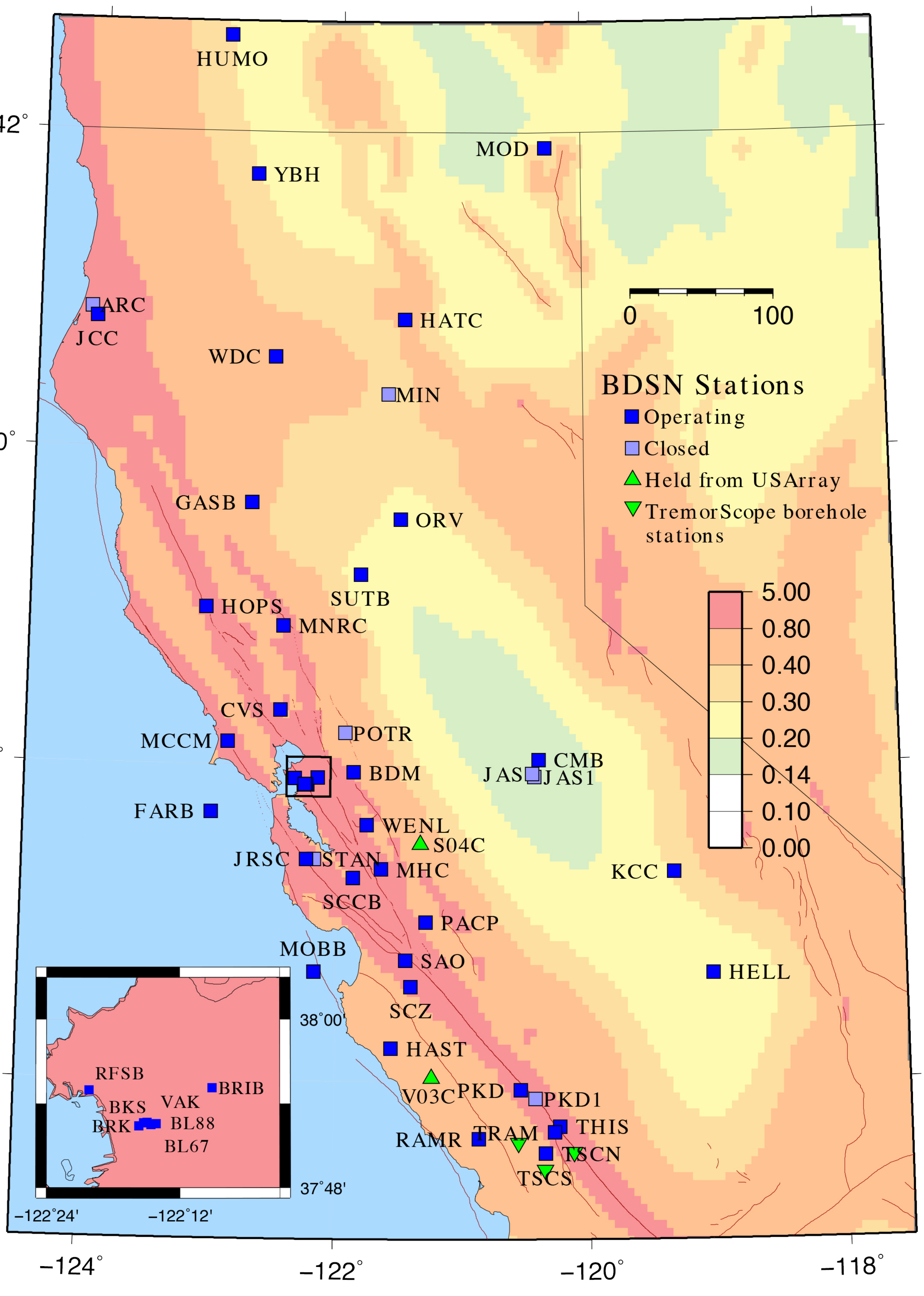


Figure 4.1.1: Map illustrating the distribution of BDSN stations in Northern and Central California. In the inset map, the order of the stations from left to right is: RFSB, BRK, BL88, VAK, BL67, BKS, BRIB.

1 Berkeley Digital Seismic Network (BDSN)

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 4.1.1 and Table 4.1.1). The network is designed to monitor regional seismic activity as well as to provide high quality data for research in regional and global broadband seismology.

Since 1991, the BDSN has grown from the original three broadband stations installed in 1986–87 (BKS, SAO, MHC) to 40 stations, including an ocean-bottom seismometer in Monterey Bay (MOBB). We take particular pride in high quality installations, which often involve 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 and problems. Since 2013, our field and operation efforts have been directed toward the installation of stations for the TremorScope project (see Research Section 2.34) and, of course, upgrades, maintenance and repair as necessary. Engineering and research efforts were also devoted to several projects to test instrumentation (see Operational Section 4.5). In the past year, we huddle-tested eight Quanterra environmental add-ons with SETRA pressure sensors, the QEP; recorded data from tilt meters and compared it to signals from broadband horizontal sensors; and compared accelerometers from several manufacturers.

The expansion of our network to increase the density of state-of-the-art strong motion/broadband seismic stations and to improve the joint earthquake notification system in this seismically hazardous region one of BSL's long term goals is coordinated with other institutions and is contingent on the availability of funding. With equipment provided by Lawrence Berkeley National Laboratory (LBNL), we continue to work toward installing a station in the Lawson adit on the UCB campus, very close to the fault. This effort is close to bearing fruit. We also continue our efforts to install all the stations of the TremorScope project funded by the Gordon and Betty Moore Foundation (see Section 2.34). As part of this exciting project for monitoring nonvolcanic tremor sources along the San Andreas Fault south of Parkfield, the BDSN is being augmented by a network of four high-quality borehole stations and four surface stations. All four surface stations are now installed and are collecting data. Finally, in the past year, we were approached by the University of California Santa Cruz (UCSC) and Geoscope (France), which have operated the station SCZ in the Coast Ranges near the city of Salinas, CA. Geoscope can no longer maintain the data logger at the station. The BSL has adopted the station, installed a new data logger, and is providing the data to UCSC.

Data quality and the integrity of the established network are at least as important as network growth, so existing network stations must be preserved. With equipment and funds from the America Recovery and Reinvestment Act (ARRA), the BSL was able to replace almost all of its old data loggers. We continue to operate broadband seismometers from the first generation, however. Some were installed more than 25 years ago. As funds become available, we upgrade their electronics and do our best to keep them operating well. We continue to exercise vigilance and to commit time and resources to repairs and upgrades as necessary.

BDSN Overview

Thirty-five BDSN sites are equipped with three-component broadband seismometers and strong-motion accelerometers, and with 24 or 26-bit digital data acquisition systems or data loggers. Three sites (BL88, RFSB and SCCB) consist of a strong-motion accelerometer and a 24-bit digital data logger. The ocean-bottom station MOBB is equipped with a three component broadband seismometer with integrated digitizer and a differential pressure gauge (DPG). Currently, the station SCZ has two broadband seismometers, a set of STS-1s and an STS-2, installed for comparison purposes. After we confirm the instrument response of the STS-1s, we will install an accelerometer in place of the STS-2, thus, SCZ instrumentation will be consistent with the rest of the BDSN. Data from all BDSN stations are transmitted to UC Berkeley using continuous telemetry, including the ocean-bottom site, MOBB. In order to avoid data loss during utility disruptions, each site has batteries to supply power for three days. 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 required for source and structure studies. Table 4.1.2 lists the instrumentation at each site.

Most BDSN stations have Streckeisen STS-1 or STS-2 three-component broadband sensors (*Wielandt and Streckeisen*, 1982; *Wielandt and Steim*, 1986).A few exceptions are: BRIB, where a Güralp CMG-3T broadband sensor contributed by LLNL is deployed in a post-hole installation; Güralp CMT-3T broadband seismometers at the new TremorScope sites; and a Güralp CMG-1T at MOBB. All stations, except the TremorScope sites and JRSC, have Kinemetrics FBA-ES-T accelerometers with ±2 g dynamic range. At TremorScope accelerometers are Güralp CMG-5Tc units, also with ±2 g dynamic range, and JRSC has Metrozet TSA-100. Since July, 2011, there are no longer any Q680, Q730, or Q4120 Quanterra data loggers in the BDSN collecting data from seismic sensors. The sites with Quanterras all have Q330, Q330HR or Q330S data loggers. The Quanterra data loggers employ FIR filters to extract data streams at a variety of sampling rates. The same is true for the Güralp DM24 digitizers at the TremorScope sites and at MOBB.

With the ARRA data logger upgrade, several conventions changed: All sites received SEED location codes, with the data logger for the broadband and strong motion sensors having the location code "00," and accelerometer channels are now designated with "HN?" rather than "HL?". Where there is a second broadband seismometer, as at YBH, it is designated with the location code "50". In addition, the BDSN stations now record

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
BDM	BK	37.954	-121.8655	219.8	34.7	1998/11 -	Black Diamond Mines, Antioch
BKS	BK	37.8762	-122.2356	243.9	25.6	1988/01 -	Byerly Vault, Berkeley
BL67	BK	37.8749	-122.2543	736.18	0	2011/04 -	LBNL Building 67, Berkeley
BL88	BK	37.8772	-122.2543	602.21	0	2011/01 -	LBNL Building 88, Berkeley
BRIB	BK	37.9189	-122.1518	219.7	2.5	1995/06 -	Briones Reservation, Orinda
BRK	BK	37.8735	-122.261	49.4	2.7	1994/03 -	Haviland Hall, Berkeley
CMB	BK	38.0346	-120.3865	697	2	1986/10 -	Columbia College, Columbia
CVS	BK	38.3453	-122.4584	295.1	23.2	1997/10 -	Carmenet Vineyard, Sonoma
FARB	BK	37.6978	-123.0011	-18.5	0	1997/03 -	Farallon Island
GASB	BK	39.6547	-122.716	1354.8	2	2005/09 -	Alder Springs
HAST	BK	36.3887	-121.5514	542	3	2006/02 -	Carmel Valley
HATC	BK	40.8161	-121.4612	1009.3	3	2005/05 -	Hat Creek
HELL	BK	36.6801	-119.0228	1140	3	2005/04 -	Miramonte
HOPS	BK	38.9935	-123.0723	299.1	3	1994/10 -	Hopland Field Stat., Hopland
HUMO	BK	42.6071	-122.9567	554.9	50	2002/06 -	Hull Mountain, Oregon
JCC	BK	40.8175	-124.0296	27.2	0	2001/04 -	Jacoby Creek
JRSC	BK	37.4037	-122.2387	70.5	0	1994/07 -	Jasper Ridge, Stanford
KCC	BK	37.3236	-119.3187	888.1	87.3	1995/11 -	Kaiser Creek
MCCM	BK	38.1448	-122.8802	-7.7	2	2006/02 -	Marconi Conference Center, Marshall
MHC	BK	37.3416	-121.6426	1250.4	0	1987/10 -	Lick Obs., Mt. Hamilton
MNRC	BK	38.8787	-122.4428	704.8	3	2003/06 -	McLaughlin Mine, Lower Lake
MOBB	BK	36.6907	-122.166	-1036.5	1	2002/04 -	Monterey Bay
MOD	BK	41.9025	-120.3029	1554.5	5	1999/10 -	Modoc Plateau
ORV	BK	39.5545	-121.5004	334.7	0	1992/07 -	Oroville
PACP	BK	37.008	-121.287	844	0	2003/06 -	Pacheco Peak
PKD	BK	35.9452	-120.5416	583	3	1996/08 -	Bear Valley Ranch, Parkfield
RAMR	BK	37.9161	-122.3361	416.8	3	2004/11 -	Ramage Ranch
RFSB	BK	37.9161	-122.3361	-26.7	0	2001/02 -	RFS, Richmond
SAO	BK	36.764	-121.4472	317.2	3	1988/01 -	San Andreas Obs., Hollister
SCCB	BK	37.2874	-121.8642	98	0	2000/04 -	SCC Comm., Santa Clara
SCZ	BK	36.598	-121.403	261	0	2013/04 -	Chualar Canyon, Santa Cruz
SUTB	BK	39.2291	-121.7861	252	3	2005/10 -	Sutter Buttes
TCHL	BK	35.68812	-120.40092	431	0	2013/06 -	Clark Property, Shandon
THIS	BK	35.714	-120.237	623	0	2012/05 -	South End of Cholame Valley, Shandon
TRAM	BK	35.67691	-120.27093	642	0	2012/12 -	Private Property, Shandon
TSCN	BK	35.544	-121.3481	476.47	0	2012/03 -	Shell Creek North, Shandon
VAK	BK	37.8775	-122.2489	266	10	2010/08 -	LBNL Building 46, Berkeley
WDC	BK	40.5799	-122.5411	268.3	75	1992/07 -	Whiskeytown
WENL	BK	37.6221	-121.757	138.9	30.3	1997/06 -	Wente Vineyards, Livermore
YBH	BK	41.732	-122.7104	1059.7	60.4	1993/07 -	Yreka Blue Horn Mine, Yreka

Table 4.1.1: Stations of the Berkeley Digital Seismic Network currently in operation. 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.

Code	Broadband	Strong-motion	Data logger	GPS	Other	Telemetry	Dial-In
BDM	STS-2	FBA-ES-T	Q330HR			FR	
BKS	STS-1	FBA-ES-T	Q330HR		QEP, E300, Baseplates	FR	X
BL67	CMG-3T	FBA-ES-T	Q330S			LAN	
BL88		FBA-ES-T	Q330S			R	
BRIB	CMG-3T	FBA-ES-T	Q330HR	X	Strainmeter, EM	FR	X
BRK	STS-2	FBA-ES-T	Q330HR			LAN	
CMB	STS-1	FBA-ES-T	Q330HR	X	QEP, E300, Baseplates	FR	X
CVS	STS-2	FBA-ES-T	Q330HR			FR	
FARB	STS-2	FBA-ES-T	Q330HR	X		R-FR/R	
GASB	STS-2	FBA-ES-T	Q330HR	X		R-FR	
HAST	STS-2	FBA-ES-T	Q330HR			R-Sat	
HATC	STS-2	FBA-ES-T	Q330HR			T1	
HELL	STS-2	FBA-ES-T	Q330			R-Sat	
HOPS	STS-1	FBA-ES-T	Q330HR	X	QEP, E300, Baseplates	FR	X
HUMO	STS-2	FBA-ES-T	Q330HR			VSAT	X
JCC	STS-2	FBA-ES-T	Q330HR			FR	X
JRSC	STS-2	TSA-100S	Q330HR	X	EM	Mi-LAN	X
KCC	STS-1	FBA-ES-T	Q330HR		QEP, E300, Baseplates	R-Mi-FR	X
MCCM	STS-2	FBA-ES-T	Q330HR			VSAT	
MHC	STS-1	FBA-ES-T	Q330HR	X		FR	X
MNRC	STS-2	FBA-ES-T	Q330HR	X		Sat	X
MOBB	CMG-1T		DM24		OCM, DPG	LAN	
MOD	STS-1*	FBA-ES-T	Q330HR	X	Baseplates	VSAT	X
ORV	STS-1	FBA-ES-T	Q330HR	X	Baseplates	FR	X
PACP	STS-2	FBA-ES-T	Q330HR			Mi/FR	
PKD	STS-2	FBA-ES-T	Q330HR	X	EM	R-Mi-T1	X
RAMR	STS-2	FBA-ES-T	Q330			R-FR	X
RFSB		FBA-ES-T	Q330HR			FR	
SAO	STS-1	FBA-ES-T	Q330HR	X	QEP, E300, Baseplates, EM	FR	X
SCCB		FBA-ES-T	Q330HR	X		FR	
SCZ	STS-1,STS-2		Q330HR		QEP, E300, Baseplates	?	?
SUTB	STS-2	FBA-ES-T	Q330HR	X		R-FR	
TCHL	CMG-3T	CMG-5TC	DM24			R-Mi	
THIS	CMG-3T	CMG-5TC	DM24			R-Mi	
TRAM	CMG-3T	CMG-5TC	DM24			R-Mi	
TSCN	CMG-3T	CMG-5TC	DM24			R-Mi	
VAK	CMG-3T	FBA-ES-T	Q330S			R	
WDC	STS-2	FBA-ES-T	Q330HR	X		FR	X
WENL	STS-2	FBA-ES-T	Q330HR			FR	
YBH	STS-1,STS-2	FBA-ES-T	Q330HR, Q330**	X	E300, Baseplates	R	X

Table 4.1.2: Instrumentation of the BDSN. Except for BL88, RFSB, SCCB, and MOBB, each BDSN station consists of collocated broadband and strong-motion sensors, with a 24 or 26-bit data logger and GPS timing. The stations BL88, RFSB, and SCCB are strong-motion only, while MOBB only has a broadband sensor. Additional columns indicate collocated GPS receivers as part of the BARD network (GPS) and additional equipment (Other), such as warpless baseplates, new STS-1 electronics (E300) or electromagnetic sensors (EM). The OBS station MOBB also has an ocean current meter (OCM) and differential pressure gauge (DPG). The main and alternative telemetry paths are summarized for each station. Abbreviations: FR - frame relay circuit, LAN - ethernet, Mi - microwave, R - radio, Sat - Commercial Satellite, T1 - T1 line, VSAT - USGS ANSS satellite link. An entry like R-Mi-FR indicates telemetry over several links, in this case, radio to microwave to frame relay. (*) During July 2013–June 2014, the STS-1 at this station was replaced by an STS-2. (**) YBH is CTBT auxiliary seismic station AS-109. It has a high-gain STS-2.

continuous data at 0.1, 1.0, 40, and 100 or 200 samples per second (Table 4.1.3}). In the past, other sample rates may have been available (see past annual reports).

When the broadband network was upgraded during the 1990s, a grant from the CalREN Foundation (California Research and Education Network) in 1994 enabled the BSL to convert data telemetry from analog leased lines to digital frame relay. The frame relay network uses digital phone circuits which support 56 Kbit/s to 1.5 Mbit/s throughput. Today, 21 of the BDSN sites rely on frame-relay telemetry for all or part of their communications system. We are looking for alternatives, as the phone companies will soon deprecate frame relay services. Other stations send their data to the data center via satellite, Internet, microwave, and/or radio (see Table 4.1.2).

As described in Operational Section 4.1, data from the BDSN are acquired centrally at the BSL. These data are used for rapid earthquake reporting as well as for routine earthquake analysis (Operational Sections 4.2 and 4.7). As part of routine quality control (Operational Section 4.5), power spectral density (PSD) analyses are performed continuously and are available on the Internet (http://www.ncedc.org/ncedc/PDF/).

The occurrence of a significant teleseism also provides the opportunity to review station health and calibration. Figure 4.1.3 displays BDSN waveforms for the M_w 8.3 earthquake that occurred off the northern coast of Chile on April 1, 2014.

Special Projects in the BDSN

TremorScope

In 2010, the Gordon and Betty Moore Foundation funded the BSL to complete an exciting project for monitoring non-volcanic tremor sources along the San Andreas Fault south of Parkfield. For this project, the BDSN is being augmented by a network of four high quality borehole stations and four surface stations. Progress on this project is described in Research Section 2.34), and in the 2013–2014 Activities section below. All four surface stations are now installed and are collecting data. Additionally, all four TremorScope boreholes were completed and cased.

The Monterey Bay Ocean Bottom Seismic Observatory (MOBB)

The Monterey Ocean Bottom Broadband observatory (MOBB) is a collaborative project between the Monterey Bay Aquarium Research Institute (MBARI) and the BSL. Supported by funds from the Packard Foundation to MBARI, from NSF/OCE, and from UC Berkeley to the BSL, its goal has been to install and operate a long-term seafloor broadband station as a first step toward extending the onshore broadband seismic network in Northern California to the seaward side of the North America/Pacific plate boundary, providing better azimuthal coverage for regional earthquake and structure studies. It also serves the important goal of evaluating background noise in near-shore buried ocean floor seismic systems, such as may be installed as part of temporary deployments of "leap-frogging" arrays (e.g. Ocean Mantle Dynamics Workshop, September 2002). The project has been described in detail in BSL annual reports since 2002 and in several publications (e.g. *Romanowicz* et al., 2003, 2006, 2009; *Taira et al., 2014).*

Sensor	Channel	Rate (sps)	Mode	FIR
BB	VH?	0.1	C	Ac
BB	LH?	1	C	Ac
BB	BH?	40	C	Ac
BB	HH?	100	C	Ca
SM	LN?	1	C	Ac
SM	BN?	20/40	C	Ac
SM	HN?	100/200	C	Ca/Ac

Table 4.1.3: Typical data streams currently acquired at BDSN stations, with channel name, sampling rate, sampling mode, and the FIR filter type. BB indicates broadband; SM indicates strong-motion; C continuous; Ac acausal; Ca causal. The HH and HN channels are now all recorded and telemetered continuously at 100 sps (200 sps for the accelerometers at the TremorScope sites) and most have causal filtering. In the past, SM channels have beennamed HL? (BL?, LL?). For past sampling rates, see earlier annual reports.

MOBB is now continuously providing data through a cable connected to the Monterey Accelerated Research System observatory (MARS, http://www.mbari.org/mars/), a seafloor node in Monterey Bay connected to a shore facility in Moss Landing by a 52 km electro-optical cable. The cable was deployed in the spring of 2007, and node installation was completed in November of 2008.

MOBB, located ~3 km from the node, was connected on February 28, 2009, through an extension cable installed by the ROV Ventana, with the help of a cable laying toolsled. Technical information about the installation and cabling are provided in past annual reports. After one year of continuous operation, the MOBB real-time telemetry ceased abruptly when the extension cable snapped as a result of repeated trawling, even though the observatory is located in a protected zone. With funds from NSF/OCE to replace the 3.2 km cable, we decided to "go the extra mile" to bury the cable to protect it better. MOBB has been online again since the cable was replaced in June 2012, as described in the 2011–2012 Annual Report. The station has been running well since then, except for "timing" problems due to the way time information is provided through the MARS node. We are working with MBARI to resolve those problems. As of 2012, we have implemented a method for removing infragravity induced noise from data of the vertical seismic channel and are exploring other means to further improve data for use in analysis. As can be seen in Figure 4.1.4, at very long periods (1.5–5 mHz) the data at MOBB are comparable with those from the other stations of the BDSN.

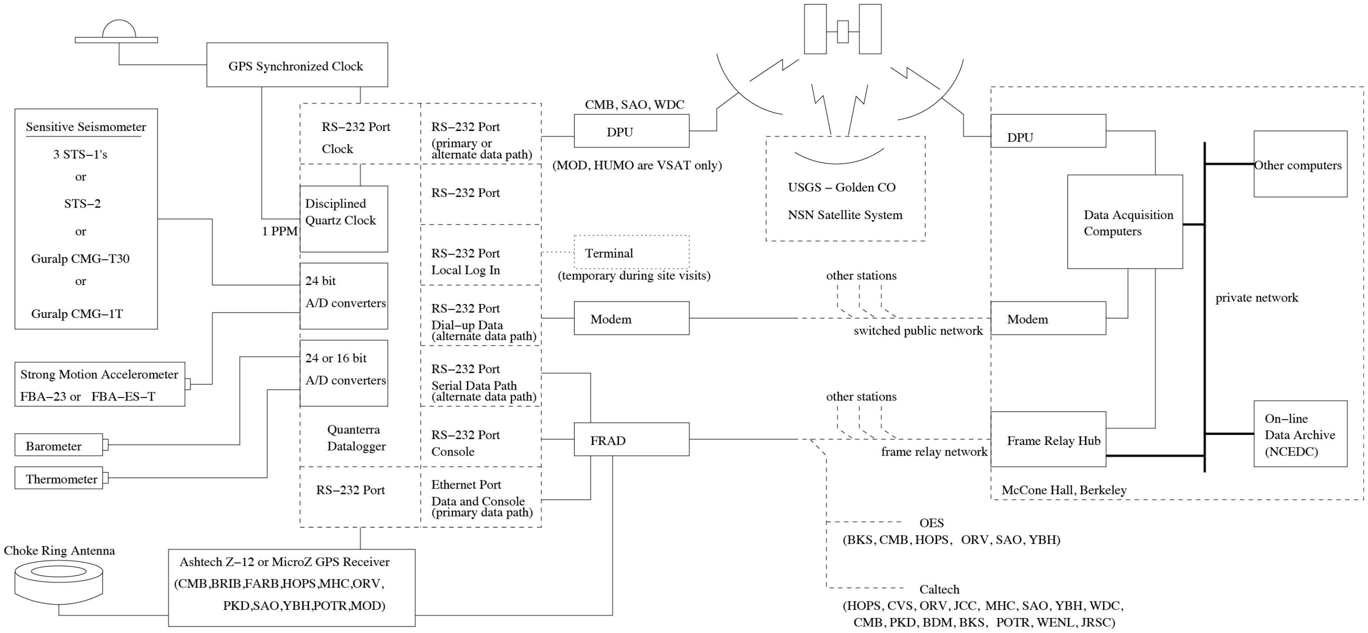


Figure 4.1.2: Schematic diagram showing the flow of data from the sensors through the data loggers to the central acquisition facilities of the BSL.

Electromagnetic Observatories

The BSL's first electromagnetic observatories were deployed in 1995, in collaboration with Dr. Frank Morrison. Well characterized electric and magnetic field measuring systems were installed at two BDSN sites along the San Andreas Fault. These reference sites, now referred to as ultra-low frequency electromagnetic (ULFEM) observatories, are collocated with seismometer sites so that the field data share the same time base, data acquisition, telemetry, and archiving systems as the seismometer outputs. The original UC Berkeley sites were installed at San Andreas Geophysical Observatory (SAO), outside Hollister, halfway between San Francisco and Parkfield; and at the Parkfield earthquake prediction experiment (PKD), 300 km south of the San Francisco Bay Area (Figure 4.1.1). Each of the two sites is equipped with three induction coils and two 100 m electric dipoles. In addition, PKD has two 200 m electric dipoles. The magnetotelluric (MT) data are continuously recorded at 40 Hz, 1 Hz and 0.1 Hz and archived at the NCEDC (Table 4.1.4). For a history of instrumentation siting, see past annual reports.

In 2004 the NSF's EarthScope program funded a Stanford-USGS-Berkeley collaboration, led by Simon Klemperer, Jonathan Glen and Darcy McPhee, to install three additional ULFEM sites within the San Francisco Bay Area. Sites were selected close to the San Andreas fault on Stanford lands at Jasper Ridge (JRSC), on Marin Headlands (MHDL), and in the East Bay near the Hayward fault on UC land near Briones Regional Park. All these three sites are significantly affected by electromagnetic noise from the BART electric train system, but were sited in the populated San Francisco Bay area on the premise that if ULFEM signals were ever detected as precursors to earthquakes, such a discovery would have greater societal benefit in a populated area than in more remote parts of California. The new instrumentation was installed at JRSC in 2004, MHDL in 2006 and BRIB in 2007. JRSC, BRIB and MHDL have three orthogonal EMI-Schlumberger magnetic coils. JRSC and BRIB each also have two independent sets of orthogonal 100 m electric dipoles, each with a shared, common electrode, an arrangement mandated by the limited number of recording channels on the Quanterra digitizing system. MHDL lacks electric sensors due to National Park Service restrictions on land access. Data at the EM/MT sites are currently fed to Quanterra data loggers synchronized in time by GPS, and sent to the BSL via dedicated communication links. The installations use proprietary electric field and magnetic field "signal conditioners" between the electrodes or magnetometers and the Quanterra digitizers.

The availability of new funding from NASA in 2009 led to a joint effort by the USGS, BSL and Stanford towards improving operation and maintenance of the EM/MT sites. BSL engineers met scientists from the USGS and Stanford at SAO in October 2008 to assess the condition of the EM/MT system. The EM coils were not working; they were removed and returned to the manufacturer. EM/MT equipment at PKD was evaluated in August 2008. There, the data logger was removed from the PKD EM/MT system and has not yet been returned. At the same time, the Stanford-USGS sites were suffering from intermittent failures, due to lack of full-time maintenance staff.

In 2008, the BSL began developing a low-cost digitizer intended to be a lower-power, lower-cost replacement for both the signal conditioners and the Quanterra. At the inception of the design process, it was hoped that this new digitizer

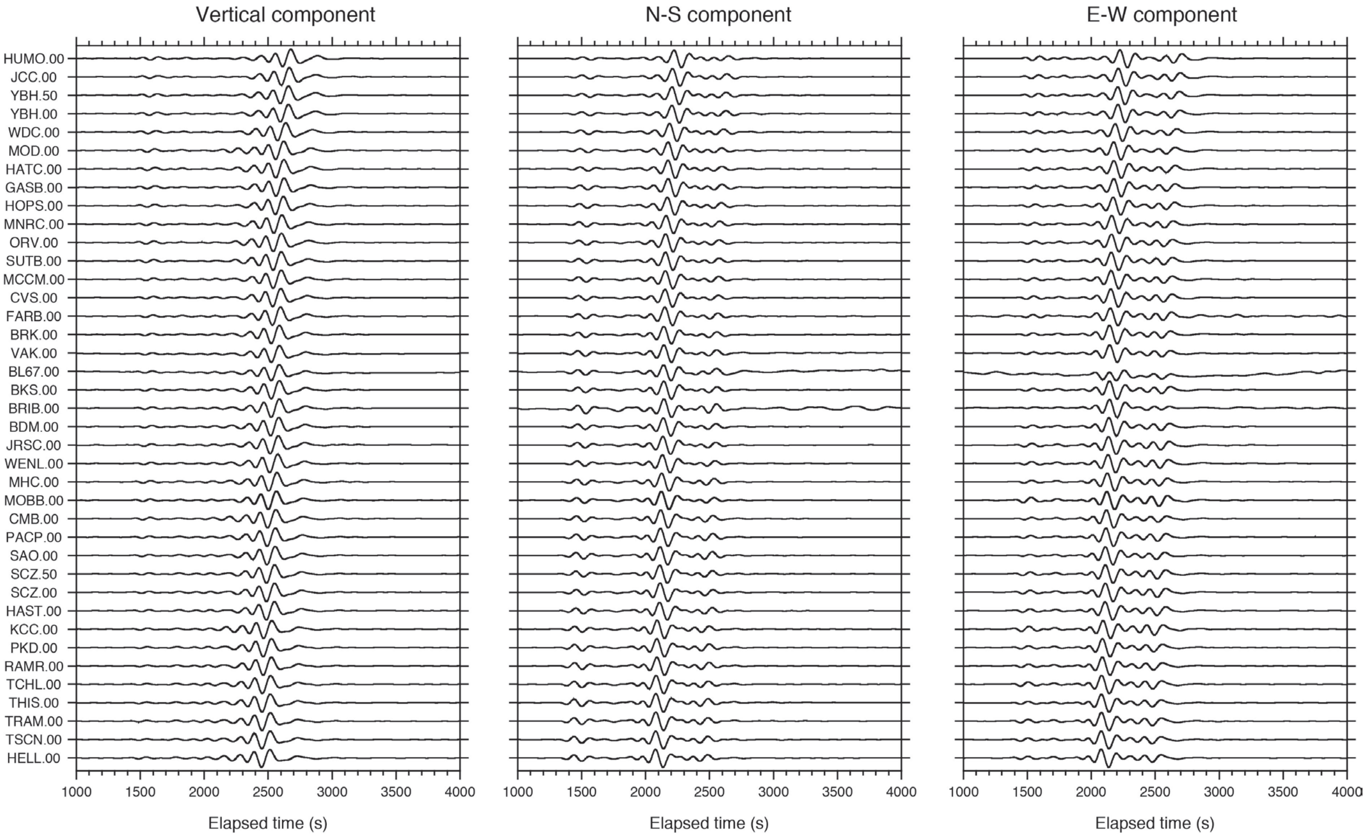


Figure 4.1.3: Long period (100–333 s period) waveforms recorded across BDSN from the M_w 8.2 teleseismic earthquake which occurred on April 1, 2014, off the northern coast of Chile at 19.610 S, 70.760 W. The panels show data from the vertical, north-south and east-west componenets, respectively. The traces are deconvolved to ground velocity, scaled by their maximum values, and ordered from bottom to top by distance from the epicenter. The highly similar waveforms recorded across the BDSN provide evidence that the broadband sensors are operating within their nominal specifications. BDSN data are archived and available at the Northern California Earthquake Data Center. This is described in detail in Operational Section 4.8.

,while not as feature-rich as commercially available data loggers, might serve both seismic and electromagnetic communities. Subsequently, the design process moved to become a Stanford-USGS responsibility. A prototype 24-bit digitizer was developed and field-tested (*Bowden et al*, 2010). A significantly modified version is being retested in the summer of 2013.

The site JRSC is now being used as a test bed for new MT field installations and electronic equipment. There, duplicate recording equipment can be installed alongside the permanent MT station to check the fidelity of new equipment. As of September 2013 the replacement ULFEM digitizer is recording data from magnetometers temporarily installed alongside the permanent magnetometers that are recorded on a Quanterra. Data from identical magnetometers recorded by the old and new systems are being compared to verify that the ULFEM digitizer has acceptable performance before it is installed at any station permanently. In the 2004–2007 original Bay Area deployments, magnetometers were buried directly inside of plastic conduit. At JRSC a new installation system has been implemented for the horizontal magnetic coils. Now, brackets are set in concrete to support plastic conduit that can be accurately leveled, and that can be drained to prevent buildup of condensation. In summer 2013 the horizontal magnetometers at MHDL, BRIB and SAO, are being reinstalled using this new system. In the original installations it was assumed that the magnetometer coils were stable electronically, and no provision was made for regular calibration. A calibration coil system has now been developed and is being tested. In this system a coil is permanently installed around the magnetometers; it will be pulsed at midday every day with a fixed voltage at known frequencies (*Connor et al.*, 2012). The calibration pulse is intended to be automatically initiated from the ULFEM digitizer. Calibration coils will be installed at JRSC, MHDL, BRIB and SAO as soon as the ULFEM digitizer is accepted to replace the existing Quanterras.

Although the Stanford-USGS-Berkeley ULFEM network will be significantly refurbished and improved as a result of summer 2013 field activities, no progress has been made on re-installing the PKD system. Existing grants from federal agencies expire in 2013, and until we succeed in receiving new grants, we anticipate no new progress in maintaining or improving recording systems, but will instead focus on data analysis to justify new grant proposals.

Sensor	Channel	Rate (sps)	Mode	FIR
Magnetic	VT?	0.1	C	Ac
Magnetic	LT?	1	C	Ac
Magnetic	BT?	40	C	Ac
Electric	VQ?	0.1	C	Ac
Electric	LQ?	1	C	Ac
Electric	BQ?	40	C	Ac

Table 4.1.4: Typical MT data streams acquired at SAO, PKD, BRIB, and JRSC with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous; Ac acausal. Data loggers for these systems have not been upgraded/replaced, but tests are ongoing with new data loggers.

2013–2014 Activities

Station Upgrades, Maintenance, and Repairs

Given the remoteness of the off campus stations, BDSN data acquisition equipment and systems are designed, configured, and installed so that they are both cost effective and reliable. As a result, there is little need for regular station visits. Nonetheless, repair, maintenance and upgrade visits are occasionally required, especially since many of the broadband seismometers installed by BSL are from the first generation and are about 25 years old.

In the summer of 2009, the USGS received ARRA funds, among other things, to upgrade and improve seismic stations operated as part of the Advanced National Seismic System (ANSS). The BSL continues to benefit from those funds, in the form of a reduction in maintenance and repair visits to our sites. We received the new model of Quanterra data logger, the Q330HR, as government-furnished equipment (GFE). Over the course of the following two years, we installed the Q330HR, replacing the old Quanterras at 25 BDSN seismic stations. In addition, under the ARRA, all remaining Kinemetrics FBA-23 accelerometers were replaced with Kinemetrics' newer, lower noise model, the FBA-ES-T. Some ARRA money was used to purchase Quanterra Environmental Packages (QEP) and SETRA pressure sensors for our quietest sites. Over the years the environmental sensors (pressure, temperature, humidity) installed at many of the sites had died. In addition, the Q330 has only six input channels, which we use for the seismometer and accelerometer components. The QEP offer additional digitizing capacity as well as rudimentary environmental sensors (pressure, temperature, humidity). We purchased the SETRA pressure sensors to ensure high quality pressure measurements for reducing long period noise in the very broadband recordings. During the Spring 2012, we installed all QEP packages and SETRA pressure sensors in a huddle test on the roof of McCone Hall. In 2013, we have installed the QEPs at BKS, CMB, HOPS, KCC, SAO and SCZ.

In addition, over the past four years, we have been able to purchase and install new electronics, the E300 from Metrozet, for our STS-1 sites. Including work in 2013, seven sites have E300s: BKS, CMB, HOPS, KCC, SAO, YBH, and the site we adopted from UCSC and Geoscope, SCZ. Funds for the E300s have come from our IRIS/GSN grant, and from our support from the California Office of Emergency Services (CalOES), and from the Federal Emergency Management Agency, through CalOES.

New Stations

TremorScope: Four TremorScope boreholes were completed and cased. Huts were constructed over boreholes to provide protection and support for solar panels. Each site has four 12 V batteries. We expect to install sensors and data loggers in this summer.

Repair, Maintenance and Upgrades

As always, some of the BSL's technical efforts were directed toward maintaining, repairing existing instrumentation, stations, and infrastructure. We have benefited greatly from the data loggers provided and installed through the ARRA upgrade, and from the installation of the E300s at some of our STS-1 sites. They allow better remote access, troubleshooting and reconfiguration. Now, field visits can be better prepared for as well as more effective. Remotely performed activities will not be reported here. They include seismometer recenters at many sites, remote calibration at sites with STS-1s and E300s and upgrades of the firmware for both Q330s and Balers at all sites.

BKS: The UDS100 was installed for E300 serial port access. The accelerometer was replaced. The TremorScope geophones were tested here (see Operational Section 4.5).

CMB: We installed the UDS100 for the E300 serial port access and the QEP, although the final configuration of this system has not yet been completed.

HOPS: The GPS clock for the Q330HR was replaced.

HELL: We have installed a cube of insulation around the STS-2. One layer of pink, one-inch thick insulating foam was placed around the sides. The STS-2 previously had no insulation other than the removable floor of the vault which sat above it. The vault has the cement floor at its bottom and a removable floor layer above the STS-2. We expect that the new insulation will reduce long period noise at this site. The batteries were also replaced.

KCC: The QEP was moved into the vault so that the temperature measurement more accurately reflects the temperatures seen by the STS-1s. In order to ensure that the pressure measured by the QEP was not filtered by the insulation surrounding the STS-1s, a 1/4" OD vinyl tube was added over the existing vinyl tube exiting the QEP housing and runs to the outside of the insulation along the side facing the tunnel wall.

PKD: The batteries were replaced.

SAO: In the past year, we had to replace the accelerometer, which was GFE and was returned to the ANSS Depot for repair. We accidentally re-oriented the accelerometer.

TSCN: The DM24 digitizer was replaced.

Perspectives for 2014–2015

We have several goals for 2014–2015. One of them is to complete an installation of separate insulation for the STS-2s at the former Transportable Array sites (HAST, HATC, RAMR, SUTB) to explore how this may reduce noise on the horizontal components. At our mini-PBO stations in the Bay Area, we will complete the adoption of their tilt and strain sensors. We already record the strain data on our GFE Basalt data loggers. Together, we developed a plan to replace the Basalt data loggers with Quanterra Q330 data loggers and QEPs. This will allow the collection of nine channels of time series data as well as air pressure data from a SETRA, and pore pressure data from the Paroscientific down-hole instrument. We are also exploring the possibility of recording data from USGS accelerometers in Parkfield that are collocated with some of our borehole stations there. This would also involve an upgrade of our radio telemetry system.

Very Long Period Data from the BDSN

Great earthquakes excite normal modes in frequency bands around 1 mHz, well below those of smaller earthquakes. The April 1, 2014, M_w 8.2 earthquake which occurred off the northern coast of Chile provided an opportunity to look at the noise levels in these bands at our broadband BDSN stations. Figure 4.1.4 shows spectra in the band from 0.15 mHz to 5.5 mHz for all our broadband stations except for HELL and SUTB due to data gaps, which have both a variety of sensors (see Table 4.1.2), and different types of installations. We are pleased to find that in this band, the normal mode signals from the majority of BDSN sites are well above the noise at all stations. We propose to further explore the performance of our stations in this band using a suite of earthquakes of various sizes.

Acknowledgements

Under Richard Allen's general supervision, Peggy Hellweg oversees the BDSN operations. Doug Neuhauser is responsible for organizing BDSN data acquisition operations, and Peggy Hellweg coordinates the engineering team. John Friday, Joshua Miller, Sarah Snyder Taka'aki Taira, and Bob Uhrhammer contribute to the operation of the BDSN. The network equipment upgrades and improvements were funded through the ARRA (American Recovery and Reinvestment Act), under USGS award number G09AC00487. The new STS-1 electronics, E300s, installed at seven of our stations, were purchased with funds from an IRIS/GSN grant and from CalOES and FEMA. The new Q330-E300 cables for KCC and YBH were purchased with funds from the IRIS/GSN grant. The TremorScope deployment is funded by Grant 2754 from the Gordon and Betty Moore Foundation.

MOBB is a collaboration between the BSL and MBARI. From the BSL, Barbara Romanowicz, Taka'aki Taira, and Doug Neuhauser participate in the project. The MBARI team is headed by Paul McGill and has included many others over the years. The MOBB effort at the BSL is supported by UC Berkeley funds. MBARI supports the dives and data recovery. The MOBB seismometer package was funded by NSF/OCE grant 9911392. The development of the interface for connection to the MARS cable is funded by NSF/OCE grant 0648302.

Taka'aki Taira, and Peggy Hellweg contributed to the preparation of this section.

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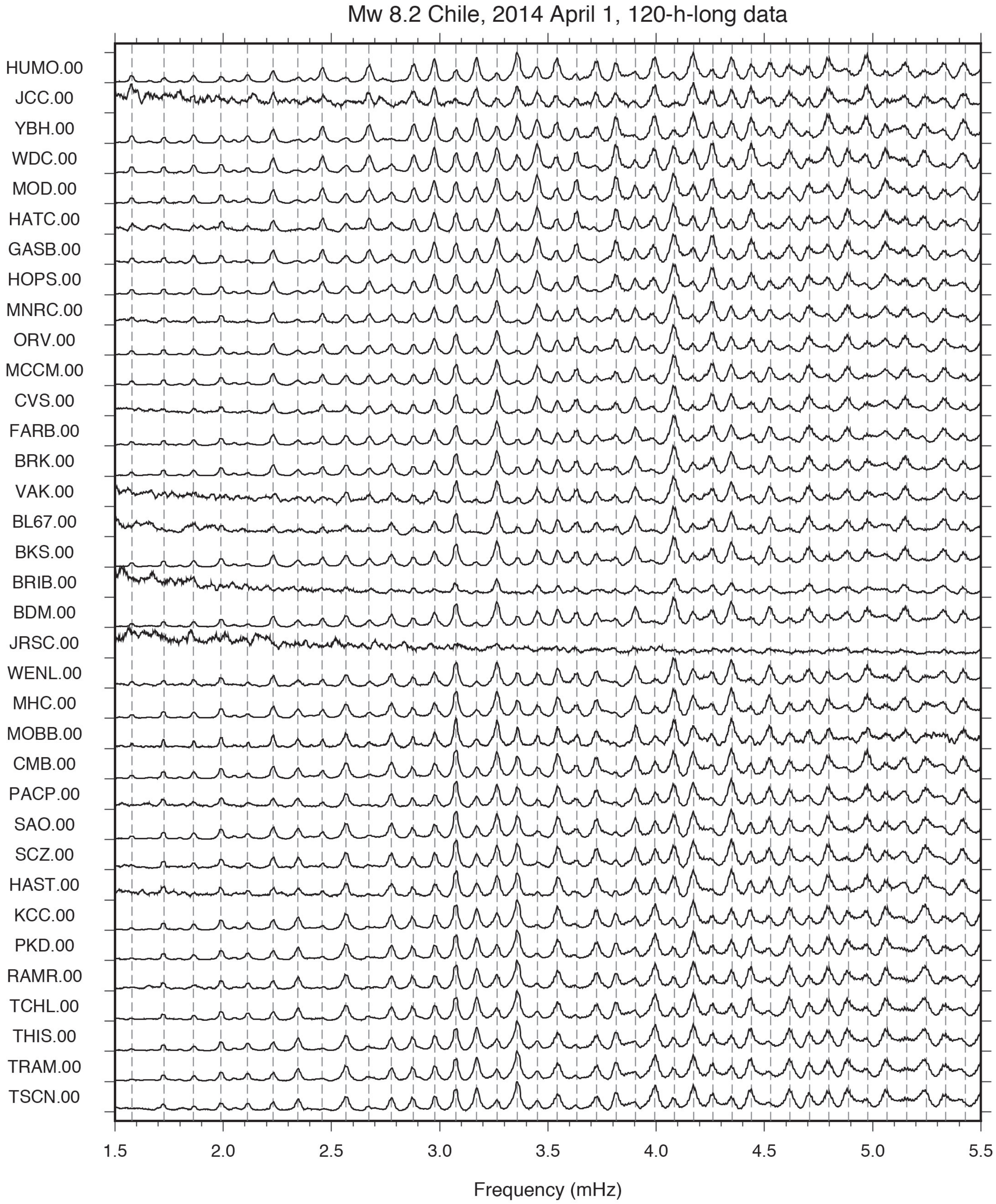

Figure 4.1.4: Amplitude spectra of the vertical component of ground acceleration for the 120-hour-long data recorded at BDSN stations following the April 1, 2014 M_w 8.2 Chile event, off its northern coast. The spectra are normalized by their maximum amplitudes. Dashed lines are expected spheroidal modes with the PREM model.

2 California Integrated Seismic Network (CISN)

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 began in the south with the TriNet Project where, Caltech, the California Geological Survey (CGS), and the USGS created a unified seismic system for Southern California. With major funding provided by the Federal Emergency Management Agency (FEMA), the California Governor's Office of Emergency Services (CalOES), and the USGS, monitoring infrastructure was upgraded and expanded, combining resources in a federal, state and university partnership. In 2000, the integration effort expanded to the entire state with the formation of the California Integrated Seismic Network (CISN, see 2000–2001 Annual Report). To this end, UC Berkeley and the USGS Menlo Park and Pasadena offices joined forces with Caltech and the CGS. The CISN is now in the thirteenth year of collaboration and its thirteenth year of funding from CalOES.

CISN Background

Organization

The organizational goals, products, management, and responsibilities of the CISN member organizations are described in the founding memorandum of understanding and in the strategic and implementation plans. To facilitate activities among institutions, the CISN has three management centers:

- Southern California Earthquake Management Center: Caltech/USGS Pasadena
- Northern California Earthquake Management Center: UC Berkeley/USGS Menlo Park
- Center for Engineering Strong Motion Data: California Geological Survey/USGS National Strong Motion Program

The Northern and Southern California Earthquake Management Centers operate as twin statewide earthquake processing centers, serving information on current earthquake activities, while the Center for Engineering Strong Motion Data is responsible for producing engineering data products and distributing them to the engineering community.

The Steering Committee, made up of two representatives from each core institution and a representative from CalOES, oversees CISN projects. The position of chair rotates among the institutions; John Parrish from CGS took over as chair of the Steering Committee in January 2013 from Ken Hudnut.

An external Advisory Committee represents the interests of structural engineers, seismologists, emergency managers, industry, government, and utilities, and provides review and oversight. The Advisory Committee is chaired by Loren Turner of Caltrans. It last met in March 2013, and the meeting for 2014 is in the process of being scheduled at the time of publication. Agendas and reports from the meetings are available on the CISN website (http://www.cisn.org/advisory).

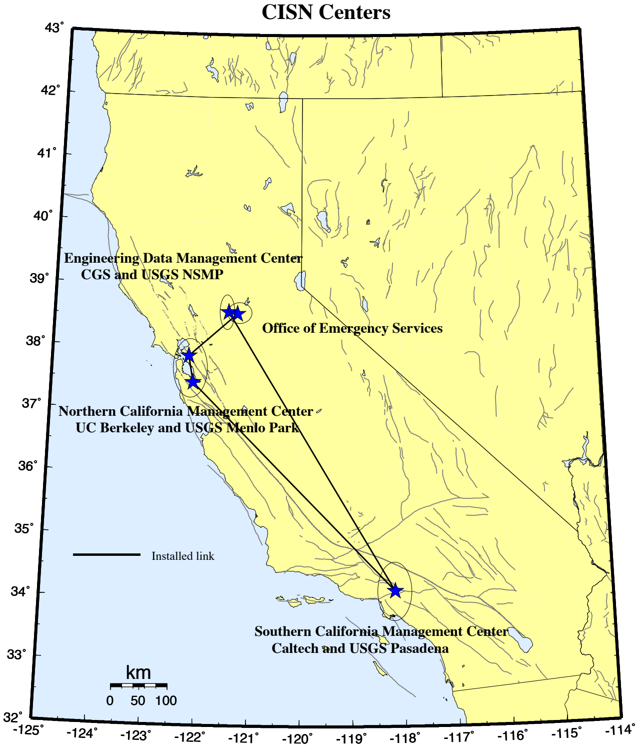

Figure 4.2.1: Map showing the geographical distribution of the CISN partners and centers. The communications "ring" is shown schematically with installed links (solid lines). It was initially a ring of dedicated T1 connections between the partners. The connections are now less robust, as reduced funding has required that the dedicated service was discontinued. Connections are now available as Internet tunnels.

The Steering Committee has commissioned other committees, including a Program Management Group to address planning and coordination, and a Standards Committee to resolve technical design and implementation issues.

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

CISN and ANSS

The USGS Advanced National Seismic System (ANSS) has developed along a regionalized model. Eight regions have been organized, with the CISN representing the California region. David Oppenheimer of the USGS represents the CISN on the ANSS National Implementation Committee (NIC).

As the ANSS moves forward, committees and working groups are established to address issues of interest. BSL faculty and staff have been involved in several working groups of the Technical Integration Committee, including Doug Dreger, Peggy Hellweg, Pete Lombard, Doug Neuhauser, Bob Uhrhammer, and Stephane Zuzlewski.

Since 2010, the software developed and implemented by the CISN for earthquake monitoring has been adopted by the ANSS, as the ANSS Quake Monitoring System (AQMS). It is now operating at many regional seismic networks throughout the United States. Since then, the CISN has expanded the membership of the CISN Standards Committees and its subcommittees by inviting interested members from other regional networks to participate in the regular conference calls, particularly when they have suggestions or need discussion of changes and improvements to the AQMS software.

CISN and CalOES

CalOES has long had an interest in coordinated earthquake monitoring in the State. The historical separation between Northern and Southern California and between strong-motion and weak-motion networks complicated earthquake response. Thus, CalOES has advocated for improving coordination and collaboration in earthquake monitoring, and supported the development of the CISN. In FY 01–02, Governor Gray Davis requested support for the CISN, to be administered through CalOES. Funding for the California Geological Survey (CGS), Caltech and UC Berkeley was made available in spring 2002, officially launching statewide coordination. After the first year, three-year contracts to UC Berkeley, Caltech, and the CGS for CISN activities were established. We have just completed year three of the fourth three-year contract (2011–2014). Unfortunately, state funding to the CISN has been decreasing, putting pressure on our earthquake monitoring and reporting activities.

Past CISN related activities are described in previous annual reports.

2013–2014 Activities

We have just completed the fifth full year of operation in the NCEMC (Northern California Earthquake Management Center) with the new suite of earthquake monitoring software. In the past, this system was called the CISN software. In 2008, it was adopted by the ANSS as the system to be used by US regional networks for their operations and earthquake reporting, and it is now called the ANSS Quake Monitoring System, or *AQMS*. *AQMS* has now been implemented by other regional networks, and BSL staff members continue to provide information and software support to the operators of those networks. The NCEMC transitioned from a hybrid system of software for earthquake monitoring and reporting to the *AQMS* software package in June 2009. The software is now operating at the BSL and in Menlo Park. CISN funding from CalOES contributed to this transition, and has also supported other software development and operational activities at the BSL during the past year as well.

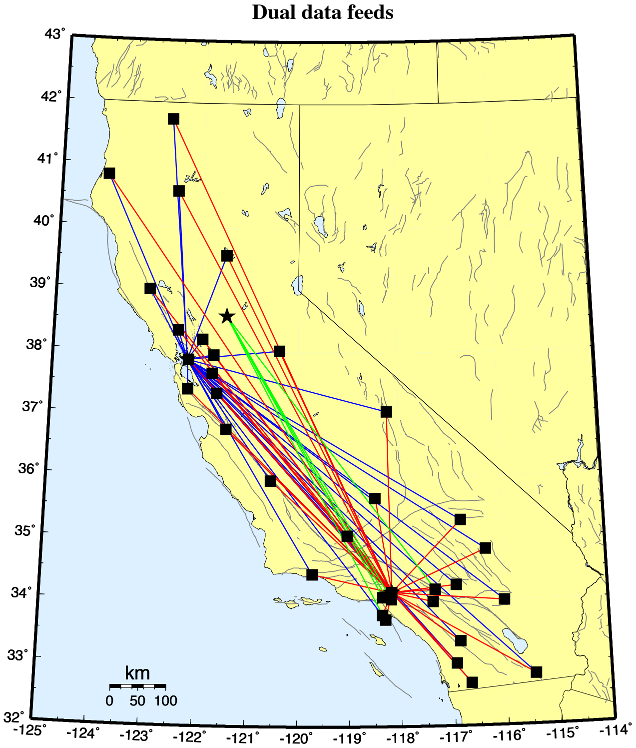

Figure 4.2.2. Map showing the original 30 stations selected to send data directly to the Northern and Southern California processing centers, and the 5 stations that send data directly to the Engineering Data Center and the Southern California processing center. Due to reductions in funding, we have converted this data feed to “data center to data center” exchange, with strong loss in robustness.

Northern California Earthquake Management Center

As part of their effort within the CISN, the BSL and the USGS Menlo Park are operating the AQMS software as the Northern California joint earthquake information system. Operational Section 4.7 describes the operation of this system and reports on progress in implementation and improvements.

For monitoring earthquakes in Northern California, the USGS Menlo Park and the BSL have improved their communications infrastructure. The BSL and the USGS Menlo Park are currently connected by two dedicated T1 circuits. One circuit is supported by CalOES funds, while the second circuit was installed in 2004–2005 (Figure 4.2.3) to support dedicated traffic between Berkeley and Menlo Park above and beyond that associated with the CISN.

Due to the decrease in funding, BSL has eliminated its second T1 for incoming data. BDSN data acquisition is now again limited to a single frame relay circuit, resulting in the reintroduction of a single point of failure.

In the long term, the BSL and USGS Menlo Park hope to be connected by high-bandwidth microwave or satellite service. Unfortunately, we have not yet been able to obtain funding for such an additional communication link, although we are exploring prospects for a very high speed radio link between the two data centers.

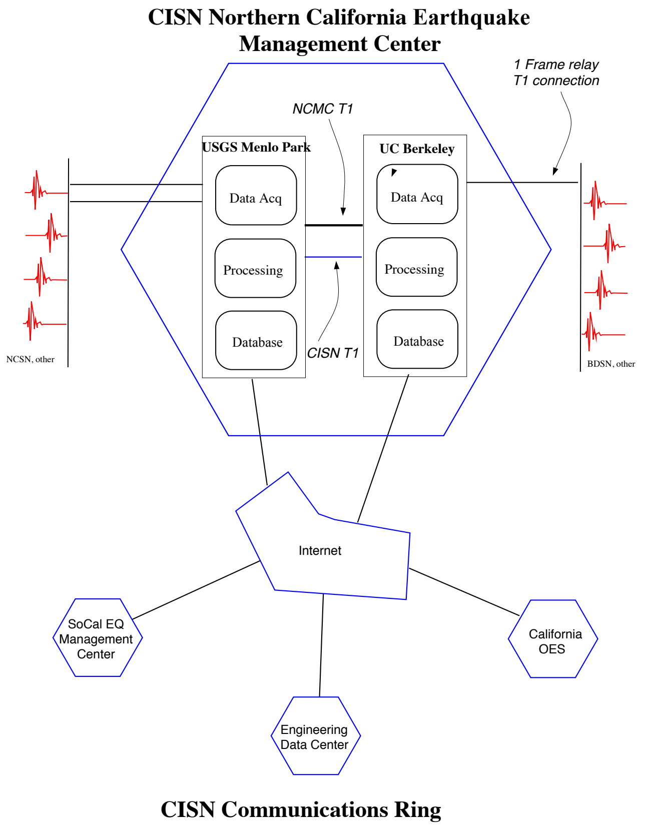

Figure 4.2.3: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley, forming the Northern California Management Center, and with other elements of the CISN.

Statewide Integration

Despite the fact that AQMS software is now operating in both Northern and Southern California, efforts toward statewide integration continue. BSL staff are involved in many elements of these efforts. The Standards Committee, chaired by Doug Neuhauser, continues to define and prioritize projects important to the ongoing development and operation of the statewide earthquake processing system and to establish working groups to address them (see minutes at http://www.cisn.org/standards/meetings.html).

Dual Station Feeds: Early in the existence of the CISN, "dual station feeds" were established for 30 stations to improve robust earthquake reporting (15 in Northern California and 15 in Southern California) (Figure 4.2.2). This year we lost this capability, mainly due to the decrease in funding from the state. We are replacing dual feeds from the stations by "data center to data center" sharing. As we do this, we are also reviewing which stations to share. Since the beginning of the dual feeds, the BSL has added many new stations to its network. The NCEMC uses data from the Southern California stations to estimate magnitudes on a routine basis. In addition, data from some the stations are used in moment tensor inversions, a computation that is sensitive to the background noise level.

Data Exchange: Part of the AQMS software allows reduced amplitude timeseries to be produced and exchanged. Currently, these timeseries are being exchanged in the NCEMC, but not yet statewide. At the end of the year, we agreed within CISN to explore sharing these parameters between Northern and Southern California. Using a common and recently improved format, the CISN partners continue to rapidly exchange observations of peak ground motion with one another following an event or a trigger. This step increases the robustness of generating products such as ShakeMap, since all CISN partners exchange data directly. This also improves the quality of ShakeMaps for events on the boundary between Northern and Southern California by allowing all data to be combined in a single map. Finally, this is a necessary step toward the goal of generating statewide ShakeMaps. In addition, datasets for events of interest to engineers are provided automatically to the Center for Engineering Strong Motion Data (CESMD) in V0 format. We are now improving data exchange with the University of Nevada, Reno, for events near the California-Nevada border, and with the Pacific Northwest Seismic Network for events near the California-Oregon border.

Software Calibration & Standardization: CISN partners have calibrated and standardized much of the software used for automatic earthquake processing and earthquake review, which is now the AQMS software. The AQMS software now serves as the real-time system operating in the NCEMC. The transition was made in June 2009.

Local Magnitudes: Since the transition to the AQMS software in Northern California in June 2009, local magnitudes are calculated throughout the state using the new logA0 function and the associated station-specific corrections for broadband/strong motion stations, and also for strong-motion only stations. We are continuing to focus on adding magnitude corrections for vertical components, whether short period or broadband, and for short period horizontal components to the new local magnitude system. A final component of the magnitude efforts is the determination of a magnitude reporting hierarchy. For the near future, each region will continue to use its own preferences for magnitude reporting.

ShakeMap: At present, ShakeMaps are generated on five systems within the CISN. Two systems in Pasadena generate "SoCal" Shakemaps; two systems in the Bay Area generate "NoCal" Shakemaps; and one system in Sacramento generates ShakeMaps for all of California. In the CISN, we evaluated the new release of the program, ShakeMap 3.5. ShakeMaps have been recalculated for all scenario events, and are about to be published. We will also soon recalculate ShakeMaps for all events in the catalog. This is necessary for two reasons. First, ShakeMap 3.5 adds additional products to the suite, such as ground motion uncertainties. Second, for ShakeMaps produced before November 2006 when the first steps toward AQMS implementation were made, there is a discrepancy between the event ID number on the ShakeMap and that in the database. In the past year, we published new Scenario Shake-

Maps, which are available on the web (http://www.cisn.org/shakemap/nc/shake/archive/scenario.html)

We have achieved the goal of improving the robustness of ShakeMap generation and delivery by CGS providing backup for all California events. The Sacramento system now uses PDL (Product Distribution Layer) to collect the authoritative event information for Northern and Southern California. The CGS also "listens" for event information from the Alaska Tsunami Warning Center as a backup, should Northern or Southern California fail to produce event information. If no map is generated by the authoritative network within 10 minutes, CGS publishes a ShakeMap. This has been tested by CGS publishing maps for events that are smaller than our usual lower limits. They have appeared on the web, associated with the correct event.

Moment Tensor Analysis: We are continuing to work toward the implementation of the capability of using data from strong motion sensors in the moment tensor interface. This is useful in large events such as the 2010 Cucapa-El Mayor earthquake in Baja California. All broadband stations out to about 600 km were clipped.

Metadata Exchange: Correct metadata are vital to CISN activities, as they are necessary to ensure valid interpretation of data. CISN is working on issues related to their reliable and timely exchange. The CISN Metadata Working Group compiled a list of metadata necessary for data processing and developed a model for their exchange. In this model, each CISN member is responsible for the metadata for its stations and for other stations that enter into CISN processing. For example, Menlo Park is responsible for the NSMP, Crest, and PG&E stations, while Caltech is responsible for data from the Anza network. At the present time, dataless SEED volumes are used to exchange metadata between the NCEMC and the SCEMC. The Metadata Working Group has made progress toward implementing Station XML format in this year. This is a format for metadata exchange. Since this vehicle is expandable, we have worked to define an "extended StationXML" that will allow exchange of a more comprehensive set of metadata than dataless SEED volumes. The extension includes parameters which are necessary for other systems, for example data in V0 format.

Standardization: The CISN's focus on standardization of software continues. The complete AQMS system is now implemented and providing real time earthquake information in the NCEMC (see Operational Section 4.7). The software has been implemented at other regional networks of the ANSS.

Earthquake Early Warning: Caltech, the BSL and the ETH Zürich have been using CISN data in real time to test earthquake early warning algorithms and to develop a demonstration earthquake early warning system (see Research Sections 2.30 and 2.29; see also http://seismo.berkeley.edu/research/early_warning, http://www.shakealert.org/ and http://www.cisn.org/eew). In 2010–2011, we achieved end-to-end processing, with events being published to a user display. The User Display is now running at the CalOES Warning Center in Sacramento, and at the location of many other beta users. They include Bay Area Rapid Transit (BART), the UC Berkeley Police Department, Google and other companies, agencies and organizations throughout California. Since August 2012, BART uses information from our EEW system to alert train operators to slow down and stop trains in the event of an earthquake.

CISN Display

CISN Display is an integrated Web-enabled earthquake notification system designed to provide earthquake information for emergency response at 24/7 operations centers. First and emergency responders, and organizations with critical lifelines and infrastructure with a need for rapid and reliable earthquake information can request an account at http://www.cisn.org/software/cisndisplay.htm.

The application provides users with maps of real time seismicity and automatically provides access to web related earthquake products such as ShakeMaps. CISN Display also offers an open source GIS mapping tool that allows users to plot freely available layers of public highways, roads and bridges, as well as private layers of organizational-specific infrastructure and facilities information. The current version of CISN Display is 1.68 at the time of writing.

Earthquake Information Distribution

The USGS hosted a workshop in October 2004 to develop plans for the installation and use of the EIDS software. Doug Neuhauser and Pete Lombard participated in this workshop, which resulted in a document outlining the steps necessary for the installation and migration of the earthquake notification system from the current Quake Data Distribution Services (QDDS) to the Earthquake Information Distribution System (EIDS). During the time EIDS was operating, shortcomings were noticed, particularly as earthquake information products became larger and more complex. During the past year, the NCEMC has transitioned from using EIDS system for publishing most of its earthquake information to the new tool, developed by the USGS, the Product Distribution Layer (PDL). This tool was initially deployed for transferring so-called add-on information, such as ShakeMaps. The BSL has been using a PDL system to publish ShakeMaps since June, 2011. During the FY 13–14 year, we worked with the USGS in Golden, CO to test and implement PDL for delivery of all real-time products, such as complete event information which includes the picks and amplitudes used for determination of location and magnitude, and other products such as moment tensors and fault plane solutions. Pete Lombard is fundamental to our progress in this effort. We currently publish all products through PDL. The BSL and NCEMC have been a "guinea pig" for implementation and is providing its codes for using PDL with AQMS to the other regional networks.

Outreach

Since FY 05–06, servers for the CISN website (http://www.cisn.org) are located at Berkeley and Caltech. The Web servers were set up so that the load could be distributed between them, providing improved access during times of high demand. With these servers, the CISN provides access to certain earthquake products directly from http://www.cisn.org. For example, ShakeMaps are now served directly from the CISN website, in addition to being available from several USGS Web servers and the CGS. The design and content of cisn.org continues to evolve. The website is an important tool for CISN outreach as well as for communication and documentation among the CISN partners. We are now serving an updated version of this website.

The CISN supports a dedicated website for emergency managers. This website provides personalized access to earthquake information. Known as "myCISN," the website is available at http://eoc.cisn.org. To provide highly reliable access, the website is limited to registered users.

As part of the CISN, the BSL contributes each year to efforts to raise awareness of earthquakes and earthquake preparedness. The BSL is a member of the Earthquake Country Alliance, a statewide organization of people, institutions and agencies associated with earthquake response and research. In the past year, we publicized and participated in the statewide ShakeOut on October 17, 2013. Due in part to our efforts, the entire UC Berkeley campus participated in it as well. We are now working toward the statewide California ShakeOut on October 16, 2014 at 10:16 (see http://www.shakeout.org for more information and to sign up).

Acknowledgements

CISN activities at the BSL are supported by funding from the California Office of Emergency Services (CalOES). Richard Allen and Peggy Hellweg are members of the CISN Steering Committee. Peggy Hellweg and Doug Neuhauser are members of the CISN Program Management Group, and Peggy leads the CISN project at the BSL with support from Doug Neuhauser. Doug Neuhauser is chair of the CISN Standards Committee, which includes Peggy Hellweg, Ivan Henson, Pete Lombard, Taka'aki Taira, and Stephane Zuzlewski as members.

Because of the breadth of the CISN project, many BSL staff members have been involved, including: John Friday, Peggy Hellweg, Ivan Henson, Ingrid Johanson, Pete Lombard, Joshua Miller, Doug Neuhauser, Charley Paffenbarger, Sarah Snyder, Taka'aki Taira, Stephen Thompson, Bob Uhrhammer, and Stephane Zuzlewski.

Peggy Hellweg contributed to this section. Additional information about the CISN is available through reports from the Program Management Group.

3 Northern Hayward Fault Network

Introduction

Complementary to the regional surface broadband and short-period networks, the Hayward Fault Network (HFN) (Figure 4.3.1 and Table 4.3.1) is a deployment of borehole-installed, wide-dynamic range seismographic stations along the Hayward Fault and throughout the San Francisco Bay toll bridge system. Development of the HFN was initiated through a cooperative effort between the BSL (Berkeley Seismological Laboratory) and the USGS, with support from the USGS, Caltrans, EPRI, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL (Lawrence Livermore National Laboratory), and LBNL (Lawrence Berkeley National Laboratory). The project's objectives included an initial characterization phase followed by a longer term monitoring effort using a backbone of stations from among the initial characterization station set. Funding from Caltrans, has, in the past, allowed for some continued expansion of the backbone station set for additional coverage in critical locations.

The HFN consists of two components. The Northern Hayward Fault Network (NHFN), operated by the BSL, consists of 29 stations in various stages of development and operation. These include stations located on Bay Area bridges, at free-field locations, and now at sites of the Mini-PBO (mPBO) project (installed with support from NSF and the member institutions of the mPBO project). The NHFN is considered part of the Berkeley Digital Seismic Network (BDSN) and uses the network code BK. The Southern Hayward Fault Network (SHFN) is operated by the USGS and currently consists of five stations. This network is considered part of the Northern California Seismic Network (NCSN) and uses the network code NC. The purpose of the HFN is fourfold: 1) to contribute operational data to the Northern California Seismic System (NCSS) for real-time seismic monitoring, for response applications, and for the collection of basic data for long-term hazards mitigation; 2) to substantially increase the sensitivity of seismic data to low amplitude seismic signals; 3) to increase the recorded bandwidth for seismic events along the Hayward Fault; and 4) to obtain deep bedrock ground motion signals at the bridges from more frequent, small to moderate sized earthquakes.

In addition to the NHFN's contribution to real time seismic monitoring in California, the mix of deep NHFN sites at near- and far-field sites and the high sensitivity (high signal to noise) and high frequency broadband velocity and acceleration data recorded by the NHFN also provide unique data for a variety of scientific objectives, including: a) investigating bridge responses to deep strong ground motion signals from real earthquakes; b) obtaining a significantly lower detection threshold for microearthquakes and possible nonvolcanic tremor signals in a noisy urban environment; c) increasing the resolution of the fault zone seismic structure (e.g., in the vicinity of the Rodgers Creek/Hayward Fault step over); d) improving monitoring of spatial and temporal evolution of background and repeating seismicity (to magnitudes below *M*0) to look for behavior indicating the nucleation of large, damaging earthquakes and to infer regions and rates of deep fault slip and slip deficit accumulation; e) investigating earthquake and fault scaling, mechanics, physics, and related fault processes; f) improving working models for the Hayward fault; and g) using these models to make source-specific response calculations for estimating strong ground shaking throughout the Bay Area.

Below, we focus primarily on activities associated with BSL operations of the NHFN component of the HFN.

NHFN Overview

The initial characterization period of HFN development ended in 1997. During that period, the NHFN sensors initially provided signals to on site, stand alone Quanterra Q730 and RefTek 72A-07 data loggers, and manual retrieval and download of data tapes was required. Also during the characterization period, the long term monitoring phase of the project began, involving the gradual transition of backbone monitoring sites to 24-bit data acquisition and communication platforms with data telemetry to the BSL.

Over the years, Caltrans has provided additional support for the upgrade of some non-backbone sites to backbone operational status and for the addition of several entirely new sites into the monitoring backbone. Efforts at continued expansion have been stymied due to propriety issue disputes between Caltrans and U.C. Berkeley at the administrative level. In February of 2007, the stations of the mPBO project were also folded into the NHFN monitoring scheme, increasing the NHFN by five sites.

Of the 29 stations considered part of the NHFN history, nine (E17B, E07B, YBAB, W05B, SAFB, SM1B, DB1B, DB2B, DB3B) are non-backbone stations and were not originally envisioned as long term monitoring stations. Because the borehole sensor packages at these sites could not be retrieved (having been grouted in downhole), the sites were mothballed for possible future reactivation. Support for reactivation of two of these mothballed sites (W05B and E07B) was eventually forthcoming and their reactivation is currently planned, pending completion of the Bay Bridge retrofit and resolution of the propriety issued mentioned above. Efforts at acquiring funds for reactivation/upgrade of additional mothballed sites are also pending for similar reasons.

Twelve of the remaining 20 stations are currently operational (VALB, PETB, CMAB, HERB, BRIB, RFSB, SM2B, SVIN, MHDL, SBRN, OXMT, RB2B). Operation of an additional site (OHLN) has been temporarily interrupted due to outside parties severing the power cable during local construction. Restoration of normal operations is will happen once repairs are made at the site. Operation of our site outside the Cal Memorial Stadium (CMSB) was also interrupted, due to accidental destruction of the borehole site during retrofit work on the stadium. Respon-

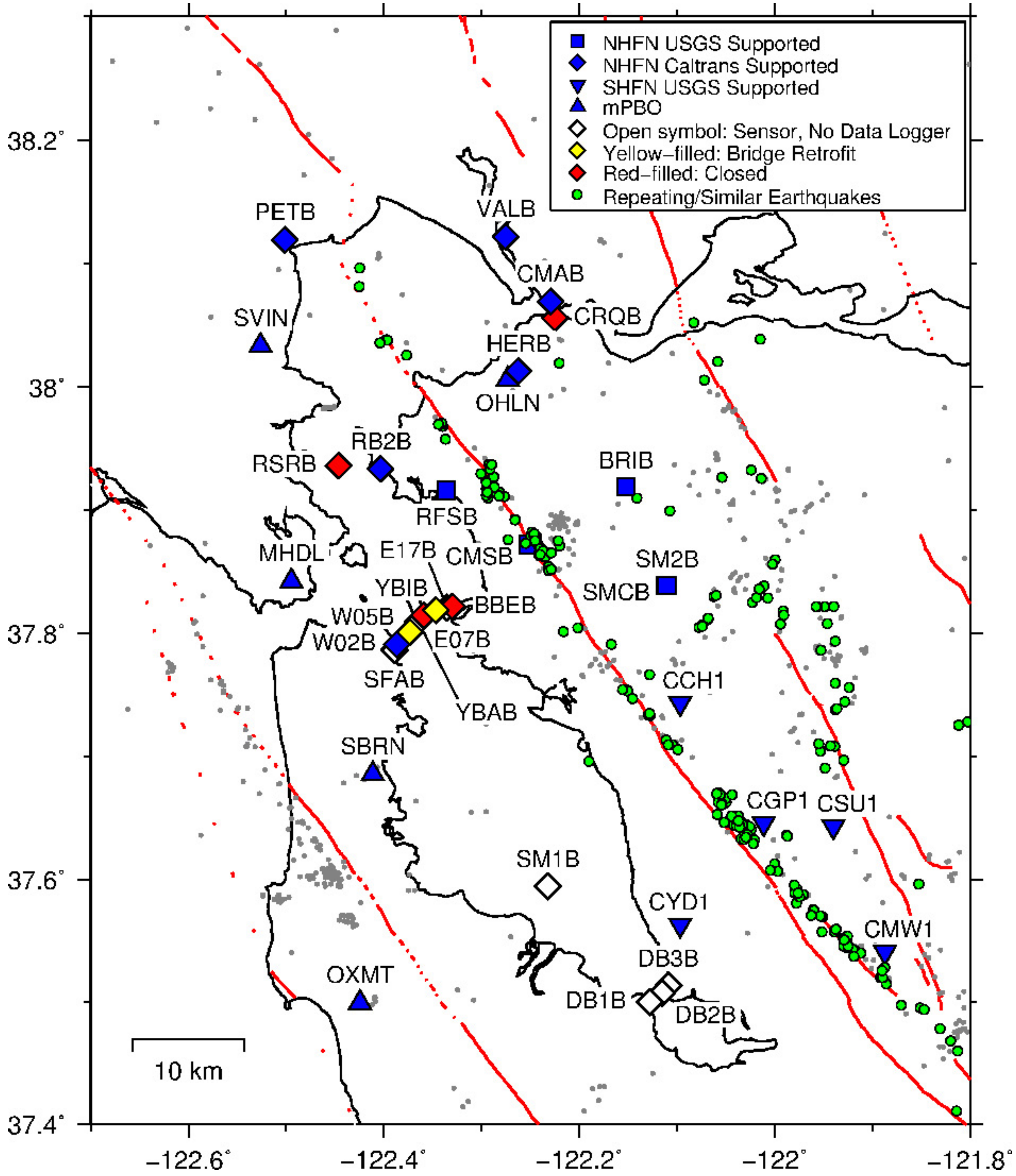

Figure 4.3.1: Map of HFN and mini-PBO stations. Diamonds are NHFN stations operated by the UC Berkeley Seismological Laboratory (BSL). Squares are BSL NHFN operated sites currently funded by the USGS. Inverted triangles are USGS SHFN sites. Triangles are former mini-PBO stations now part of the NHFN, operated by the BSL and funded by the USGS. Blue are currently operational stations. Red are stations that recorded data in the past but are now closed, either due to replacement by higher quality installations (CRQB, SMCB) or due to complications and/or damage from earthquake retrofit activity on Bay Area bridges (RSRB, BBEB, YBIB). The color yellow represents sites whose installation is suspended pending completion of the Bay Bridge retrofit (W05B, E07B) and resolution of Caltrans and U.C. Berkeley proprietary issues. Currently, station BBEB operates only as a telemetry repeater site due to damage from retrofit work. Open symbols represent sites having downhole sensors but are currently non-operational. These could potentially be brought on-line with funding support. Since 2007, the NHFN has been contributing arrival time picks to the Northern California Seismic System (NCSS) for location of Bay Area earthquakes. The small gray dots are double-difference real time relocations (http://ddrt.ldeo.columbia.edu/catalog/NCAeqDDRT.v201001) of events occurring this year that have made use of the NHFN picks. Green circles are locations of similar/repeating events occurring in the area (Taka'aki Taira, personal communication). Data for current and previously active NHFN and SHFN monitoring sites are all available through the NCEDC Web portal.

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
VALB	BK	38.122	-122.275	-24.5	155.8	2005/11 - current	Napa River Bridge
PETB	BK	38.119	-122.501	-30	113	2010/09 - current	Petaluma River Bridge
CMAB	BK	38.069	-122.229	0	142.2	2009/12 - current	Cal Maritime Academy
CRQB	BK	38.056	-122.225	-25	38.4	1996/07 - 2010/05	CB
HERB	BK	38.012	-122.262	-18	217	2001/09 - current	Hercules
BRIB	BK	37.919	-122.152	222.2	108.8	1995/07 - current	BR, Orinda
RFSB	BK	37.916	-122.336	-27.3	91.4	1996/02 - current	RFS, Richmond
CMSB	BK	37.872	-122.252	94.7	167.6	1995/06 - current	CMS, Berkeley
SMCB	BK	37.839	-122.112	180.9	3.4	1998/02 - 2007/06	SMC, Moraga
SM2B	BK	37.839	-122.110	200	150.9	2007/06 - current	SMC, Moraga
SVIN	BK	38.033	-122.526	-27.5	152.4	2003/08 - current	mPBO, St. Vincent's school
OHLN	BK	38.006	-122.273	-0.5	196.7	2001/11 - current	mPBO, Ohlone Park
MHDL	BK	37.842	-122.494	94.5	151.9	2006/05 - current	mPBO, Marin Headlands
SBRN	BK	37.686	-122.411	4	161.5	2002/08 - current	mPBO, San Bruno Mtn.
OXMT	BK	37.499	-122.424	209.1	194.3	2003/12 - current	mPBO, Ox Mtn.
BBEB	BK	37.822	-122.330	-30.8	182.9	2002/09 - 2007/11	BB, Pier E23
E17B	BK	37.821	-122.335	TBD	160	1995/08 - unknown *	BB, Pier E17
E07B	BK	37.818	-122.347	TBD	134	1996/02 - unknown +	BB, Pier E7
YBIB	BK	37.814	-122.359	-27	61	1996/07 - 2000/08	BB, Pier E2
YBAB	BK	37.809	-122.365	TBD	3	1998/06 - unknown *	BB, YB Anchorage
W05B	BK	37.801	-122.374	TBD	36.3	1997/10 - unknown +	BB, Pier W5
W02B	BK	37.791	-122.386	-45	57.6	2003/06 - 2011/02	BB, Pier W2
SFAB	BK	37.786	-122.389	TBD	0	1998/06 - unknown *	BB, SF Anchorage
RSRB	BK	37.936	-122.446	-48	109	1997/06 - 2001/04	RSRB, Pier 34
RB2B	BK	37.933	-122.403	-18	133.5	2009/12 - current	RSRB, Pier 58
SM1B	BK	37.594	-122.232	TBD	298	not recorded *	SMB, Pier 343
DB3B	BK	37.513	-122.109	TBD	1.5	1994/09 - 1994/11 *	DB, Pier 44
					62.5	1994/09 - 1994/09 *	
					157.9	1994/07 - unknown *	
DB2B	BK	37.507	-122.116	TBD		1994/07 - unknown *	DB, Pier 27
					189.2	1992/07 - 1992/11 *	
DB1B	BK	37.499	-122.128	TBD	0	1994/07 - 1994/09 *	DB, Pier 1
					1.5	1994/09 - 1994/09 *	
					71.6	1994/09 - 1994/09 *	
					228	1993/08 - unknown *	
CCH1	NC	37.743	-122.097	345	119	1995/06 - current	Chabot
CGP1	NC	37.645	-122.011	461	121	1995/06 - current	Garin Park
CSU1	NC	37.643	-121.940	623	124	1995/11 - current	Sunol
CYD1	NC	37.563	-122.097	114	137	1996/11 - current	Coyote
CMW1	NC	37.541	-121.887	498	155	1995/06 - current	Mill Creek

Table 4.3.1: Stations of the Hayward Fault Network. For entries with "*" and "+" in the date column, no monitoring data is available. For these sites, dates are periods when data was downloaded manually. These manually retrieved data are not available at the NCEDC, but may be available from Larry Hutchings (at LBNL). Abbreviations: 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. At the end of the initial characterization phase of the HFN project, the stations labeled with "*" were mothballed with borehole sensors remaining cemented in place. Incorporation of the "+" stations into the monitoring backbone is work in progress. Proposal to Caltrans requesting support to bring more mothballed sites into the NHFN backbone is pending. Due to damage from Bay Bridge retrofit work, station BBEB no longer records seismic data but continues to operate as a telemetry relay station. Data collection at sites CMSB and OHLN have been temporarily suspended to accommodate construction at their respective locations. W02B has been turned off due to equipment failure and lack of access.

Site	Geophone	Accelerometer	Z	H1	H2	Data Logger	Notes	Telem.
VALB	Oyo HS-1	Wilcoxon 731A	-90	336	246	Q330		FR
PETB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Q330		FR/Rad.
CMAB	Oyo HS-1	Wilcoxon 731A	-90	161	251	BASALT		Rad./VPN
CRQB	Oyo HS-1	Wilcoxon 731A	-90	68	338	None at Present		FR
HERB	Oyo HS-1	Wilcoxon 731A	-90	160	70	Q4120		FR
BRIB	Oyo HS-1	Wilcoxon 731A	-90	79	169	BASALT	Acc. failed, Dilat.	FR
RFSB	Oyo HS-1	Wilcoxon 731A	-90	346	256	BASALT		FR
CMSB	Oyo HS-1	Wilcoxon 731A	-90	19	109	Q4120		FR
SMCB	Oyo HS-1	Wilcoxon 731A	-90	76	166	None at present	Posthole	FR
SM2B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	BASALT		FR
SVIN	Mark L-22		-90	319	49	BASALT	Tensor.	FR/Rad.
OHLN	Mark L-22		-90	300	30	BASALT	Tensor.	FR
MHDL	Mark L-22		-90	64	154	BASALT	Tensor.	FR
SBRN	Mark L-22		-90	6	96	BASALT	Tensor.	FR
OXMT	Mark L-22		-90	120	210	BASALT	Tensor.	FR
BBEB	Oyo HS-1	Wilcoxon 731A	-90	19	109	None at present	Acc. failed	Radio
E17B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
E07B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
YBIB	Oyo HS-1	Wilcoxon 731A	-90	257	347	None at present	Z geop. failed	FR/Rad.
YBAB	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
W05B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
W02B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		Radio
SFAB	None	LLNL S-6000	TBD	TBD	TBD	None at present	Posthole	
RSRB	Oyo HS-1	Wilcoxon 731A	-90	50	140	None at present	2 acc. failed	FR
RB2B	Oyo HS-1	Wilcoxon 731A	-90	252	162	Q4120	1 acc. failed	FR
SM1B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
DB3B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present	Acc. failed	
DB2B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present		
DB1B	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	None at present	Acc. failed	
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
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
CMW1	Oyo HS-1	Wilcoxon 731A	-90	TBD	TBD	Nanometrics HRD24	Dilat.	Radio

Table 4.3.2: Instrumentation of the HFN. Every HFN downhole package consists of collocated three-component geophones and accelerometers, with the exception of mPBO sites which have only three-component geophones and are also collecting tensor strainmeter data. ix HFN sites also have dilatometers (Dilat.). The five SHFN sites have Nanometrics data loggers with radio telemetry to the USGS and eventually from there to the NCEDC for archiving. Currently, six NHFN sites have Quanterra data loggers, eight have been upgraded with ARRA funding and one (CMAB) with Caltrans funding to BASALT data loggers with local storage capacity. Of these 15 sites, 12 are currently telemetering continuous data to the BSL for archiving at the NCEDC. The sites CMSB and OHLN have been temporarily shutdown due to construction at their respective locations. Site W02B has been turned off due to equipment failure and lack of access for maintenance. Five additional backbone sites have been decommissioned for reasons ranging from the sites' replacement with nearby higher quality installations (SMCB, CRQB) to irreparable site damage by outside influences such as bridge retrofit activity and construction (BBEB, YBIB, RSRB). Station BBEB, however, continues to operate as a telemetry relay site. The component orientation of the sensors are as follows: vertical (Z) is up; horizontals (H1 and H2): azimuthal direction of positive counts in degrees clockwise from north and are given when known or labeled.

Sensor	Channel	Rate (sps)	Mode	FIR
Accelerometer	CL?	500	T	Ca
Accelerometer	CN?	500	T	Ca
Accelerometer	HL?	200	C	Ca
Accelerometer	HL?	100	C	Ca
Accelerometer	HN?	200	C	Ca
Accelerometer	BL?	20	C	Ac
Accelerometer	BN?	20	C	Ac
Accelerometer	LL?	1	C	Ac
Accelerometer	LN?	1	C	Ac
Geophone	DP?	500	T,C	Ca
Geophone	EP?	200	C	Ca
Geophone	EP?	100	C	Ca
Geophone	BP?	20	C	Ac
Geophone	SP?	20	C	Ac
Geophone	LP?	1	C	Ac

Table 4.3.3: Typical data streams acquired at NHFN sites, with channel name, sampling rate, sampling mode, and FIR filter type. C indicates continuous, T triggered, Ca causal, and Ac acausal. Typically, the DP1 continuous channel is archived and the remaining high sample rate data (i.e., CL?, CN?, DP2 and DP3 channels) are archived as triggered snippets. As telemetry options improve, progress is being made towards archiving higher sample rate and continuous data on more channels. Prior to September 2004, only triggered data was archived for all high sample rate channels. Of the stations that are currently operational, CMAB, HERB, BRIB, RFSB, CMSB, SM2B, W02B, and RB2B record at maximum sample rates of 500 Hz; VALB and PETB at maximum 200 Hz; and mPBO sites (SVIN, OHLN, MHDL, SBRN, OXMT) at maximum 100 Hz.

sibility for the destruction was identified and funds recovered to drill a new borehole in the same area. Drilling was completed in Sept. of 2013. Acquisition of funds for replacement of sensors and cable are currently under negotiation. Operation of station W02B on the western span of the Bay Bridge has been suspended due to the cessation of access to the site previously provided by Caltrans. Access is no longer available due to proprietary issues between Caltrans and U.C. Berkeley.

The operational sites include the five stations folded in from the mPBO project. The operational sites telemeter seismic data continuously into the BSL's BDSN processing stream with subsequent archival in the Northern California Earthquake Data Center (NCEDC).

Six of the 20 stations have been decommissioned for various reasons ranging from the sites' replacement with nearby higher quality installations (SMCB, CRQB) to irreparable site damage by outside influences such as bridge retrofit activity and construction (BBEB, YBIB, RSRB). Station BBEB, however, continues to be operational as a possible telemetry relay site for W02B should access to that site become available.

Installation/Instrumentation

The NHFN Sensor packages are generally installed at depths ranging between 100 and 200 m, the non-backbone, non-operational Dumbarton Bridge sites are exceptions with sensors at multiple depths (Table 4.3.1). The five former mPBO sites that are now part of the NHFN have three-component borehole geophone packages. Velocity measurements for the mPBO sites are provided by Mark Products L-22 2 Hz geophones (Table 4.3.2). All the remaining backbone and non-backbone NHFN sites have six-component borehole sensor packages. The six-component packages were designed and fabricated at LBNL's Geophysical Measurement Facility and have three channels of acceleration, provided by Wilcoxon 731A piezoelectric accelerometers, and three channels of velocity, provided by Oyo HS-1 4.5 Hz geophones.

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.

Currently five of the NHFN backbone sites have Quanterra data loggers, and nine of the sites have been upgraded with BASALT data loggers. When operational, all 14 of these sites telemeter continuously to the BSL. Signals from these stations are digitized at a variety of data rates up to 500 Hz at 24-bit resolution (Table 4.3.3). The data loggers employ causal FIR filters at high data rates and acausal FIR filters at lower data rates (Table 4.3.3).

Data Rates and Channels

Because of limitations in telemetry bandwidth and local disk storage, 6 of the 9 (excluding CMAB, VALB and PETB) six-component NHFN stations transmit maximum 500 Hz data continuously for only one geophone channel (i.e., when functional, on their vertical channel). Triggered 500 Hz data for three additional channels with 180-second snippets are also transmitted. Station VALB also continuously transmits data from only four channels, however, at a maximum of 200 Hz sampling. PETB transmits maximum 200 Hz data continuously on all six channels (three geophone, three accelerometer), and CMAB transmits maximum 500 Hz data continuously on all six channels. Continuous data for the channels of all 9 of these stations are also transmitted to the BSL at reduced sampling rates (20 and 1 sps). A Murdock, Hutt, and Halbert (MHH) event detection algorithm (*Murdock and Hutt*, 1983) is operated independently at each station on 500 sps data for trigger determinations. Because the accelerometer data is generally quieter, the MHH detections are made locally using data from the Wilcoxon accelerometers when possible. However, there is a tendency for these powered sensors to fail, and, in such cases, geophone channels are substituted for the failed accelerometers. The five mPBO-originated sites all transmit their three-cmponent continuous geophone data streams to the BSL at 100, 20, and 1 sps.

Integration with the NCSS, SeisNetWatch, and SeismiQuery

The NHFN is primarily a research network that complements regional surface networks by providing downhole recordings of very low amplitude seismic signals (e.g., from micro earthquakes or nonvolcanic tremor) at high gain with high frequencies and low noise. In addition, data streams from the NHFN are also integrated into the Northern California Seismic System (NCSS) real-time/automated processing stream for response applications and collection of basic data for long term hazards mitigation. The NCSS is a joint USGS (Menlo Park) and Berkeley Seismological Laboratory (BSL) entity with earthquake reporting responsibility for Northern California, and data from networks operated by both institutions are processed jointly to fulfill this responsibility. Through this integration, the NHFN picks, waveforms, and NCSS event locations and magnitudes are automatically entered into a database where they are immediately available to the public through the NCEDC and its DART (Data Available in Real Time) buffer. The capability for monitoring state of health information for all NHFN stations using SeisNetWatch also exists, and up-to-date dataless SEED formatted metadata is made available through the NCEDC with the SeismiQuery software tool.

Station Maintenance

Identifying network maintenance issues involves, in part, automated and semi-automated tracking of power, telemetry and data gaps. In addition, regular inspection of the seismic waveforms and spectra are carried out on samples of background noise and of significant local, regional and teleseismic earthquakes. These efforts are carried out to identify problems that can result from a variety of operational issues including changes in background noise levels from anthropogenic sources, ground loops, failing, damaged or stolen instrumentation, and power and telemetry issues. Troubleshooting and remediation of such problems are carried out through a coordinated effort between data analysts and field engineers.

In addition to routine maintenance and trouble shooting efforts, performance enhancement measures are also carried out. For example, when a new station is added to the NHFN backbone, extensive testing and correction for sources of instrumental noise (e.g., grounding related issues) and telemetry throughput are carried out to optimize the sensitivity of the station. Examples of maintenance and enhancement measures that are typically performed include: 1) testing of radio links to ascertain reasons for unusually large numbers of dropped packets; 2) troubleshooting sporadic problems with excessive telemetry dropouts; 3) manual power recycle and testing of hung data loggers; 4) replacing blown fuses or other problems relating to dead channels identified through remote monitoring at the BSL; 5) repairing telemetry and power supply problems when they arise; and 6) correcting problems that arise due to various causes, such as weather or cultural activity.

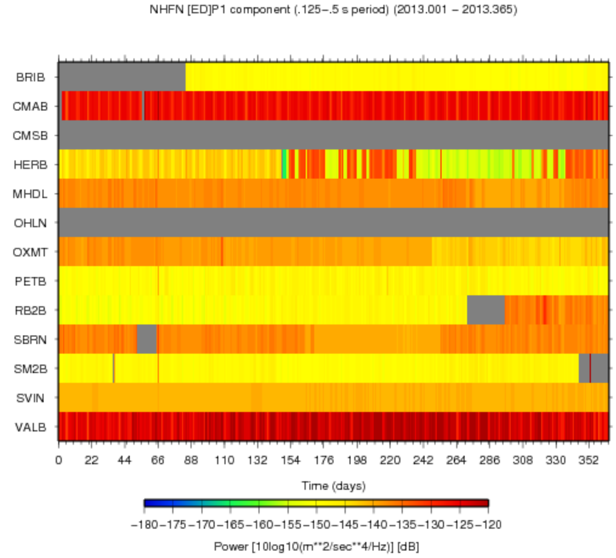

Figure 4.3.2: A summary of plots showing typically observed background noise PSD levels for the vertical DP1/EP1 channels of NHFN borehole stations for 2013. The mean PSD (dB) ranking (lowest to highest) of the non-mPBO stations (top panel) in operation at the time given at 3 Hz obtained from all available 2013 data on these channles are:
BRIB.BK.DP1 -141.885
SM2B.BK.DP1 -139.141
SVIN.BK.EP1 -138.458
PETB.BK.EP1 -136.895
OXMT.BK.EP1 -135.874
MHDL.BK.EP1 -135.736
SBRN.BK.EP1 -133.164
RB2B.BK.DP1 -127.971
HERB.BK.DP1 -126.818
CMAB.BK.DP1 -117.250
VALB.BK.EP1 -111.645
RFSB.BK.DP1 -107.407
PSDs for HFN/mPBO for the following stations are not available: CMSB (closed) and OHLN (power issue) due to construction. Variations in PSD noise among the stations are generally attributable to the stations' proximity to different cultural noise sources such as freeways or train tracks, differences in depth of sensor installation, or to differences in local geologic conditions.

Quality Control

Power Spectral Density Analyses

One commonly used quality check on the performance of the borehole installed network includes assessment of the power spectral density (PSD) distributions of background noise. We have developed and implemented an automated estimation of the power spectral density (PSD) distributions of background noise for all recorded NHFN channels and have developed summary PSD plots of these estimations to promote rapid evaluation of the noise levels through time.

Shown in Figure 4.3.2 are power spectral density (PSD) plots of background noise for 12 vertical NHFN channels in operation during 2013 for the 2–8 Hz frequency band. By

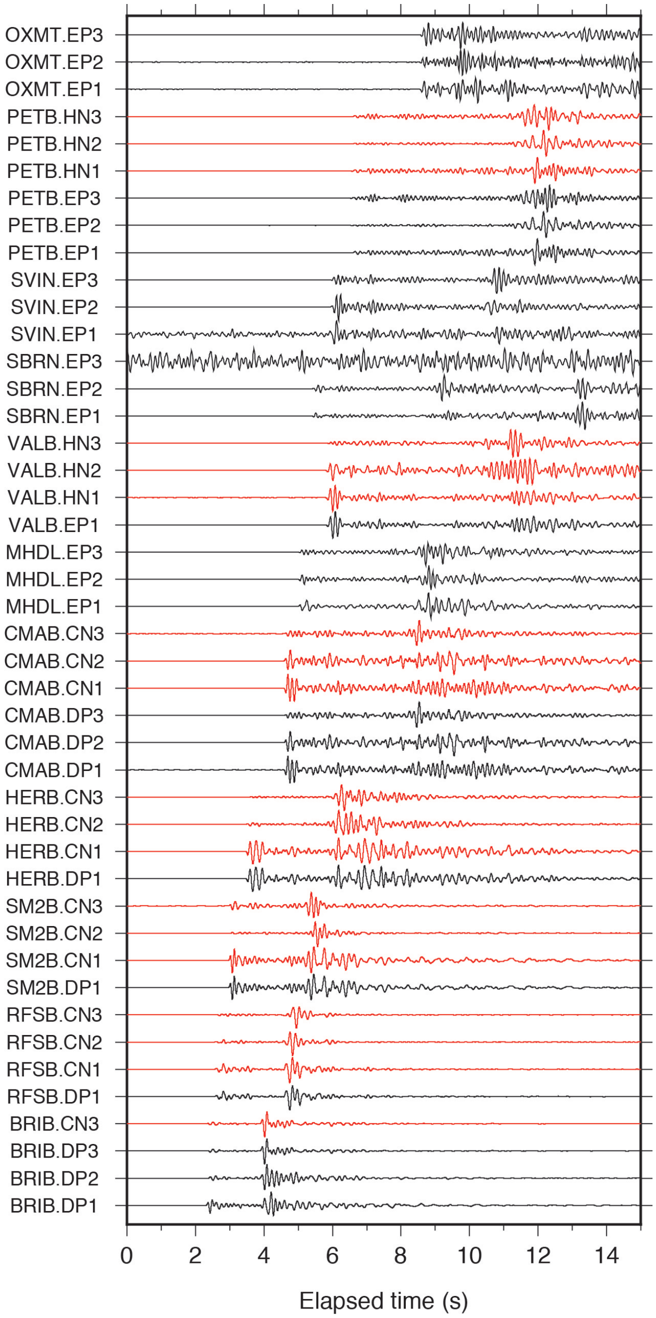

Figure 4.3.3: Plot of ground accelerations recorded on the geophones (black traces) and accelerometers (red traces) of the 11 NHFN borehole stations in operation at the time of a recent Bay Area earthquake (October 7, 2013, M3.14 near Orinda, CA). The traces are filtered with a 1–8 Hz bandpass filter, scaled by their maximum values, and ordered from bottom to top by distance from the epicenter.

continuously updating such plots in a variety of bands, we can rapidly evaluate changes in the network's station response to seismic signals across the wide band high-frequency spectrum of the borehole NHFN/mPBO sensors.

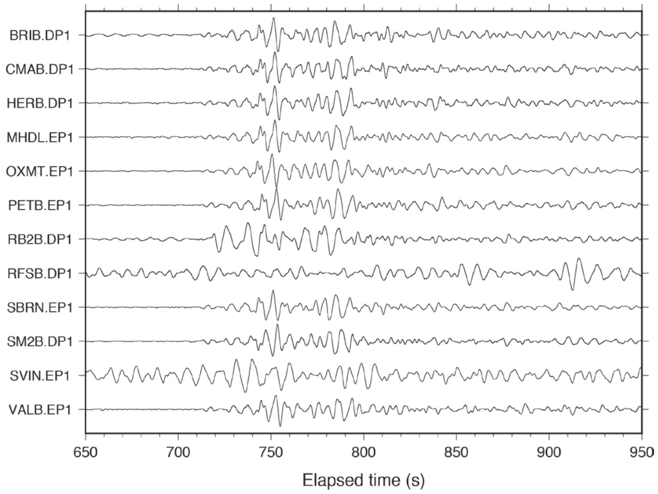

Figure 4.3.4: Plot of surface wave seismograms of the teleseismic M_w 8.2 earthquake off the northern coast of Chile (Lat.: 19.610S; Lon.: 70.760E; depth 25 km) occurring on April 1, 2014 23:46:47 (UTC) recorded on the DP1/EP1 (vertical) channels of the 12 NHFN borehole stations in operation at the time. Here, vertical component geophone (velocity) data have been 0.1–0.5 Hz bandpass filtered and normalized by the maximum amplitude for each trace.

Changes in the responses often indicate problems with the power, telemetry, or acquisition systems, or with changing conditions in the vicinity of station installations that are adversely affecting the quality of the recorded seismograms. In general, background noise levels of the borehole NHFN stations are more variable and generally higher than those of the Parkfield HRSN borehole stations (see Parkfield Borehole Network section). This is due in large part to the significantly greater cultural noise in the Bay Area and the siting of several near-field NHFN sites in proximity to Bay Area bridges. On average, the mPBO component of the NHFN sites (MHDL, OXMT, SBRN, and SVIN in Figure 4.3.2) are more consistent with each other and throughout their spectral range. This is due in large part to the greater average depth of the mPBO sensors, the locations of mPBO stations in regions with generally less industrial and other cultural noise sources, and possibly to the absence of powered sensors (i.e. accelerometers) in their borehole sensor packages. The maximum sampling rate of 100 sps at these sites also limits their spectral range to a maximum of 40 Hz, well below the 60 Hz power line noise which often becomes a problem.

One of the most pervasive problems at the other NHFN stations with higher sampling rates is power line noise (60 Hz and its harmonics at 120 and 180 Hz). This noise reduces the sensitivity of the MHH detectors and can corrupt research based on full waveform analyses. When NHFN stations are visited, the engineer at the site and a seismologist at the BSL frequently work together to identify and correct ground loop and inductive-coupling problems, which are often at the root of this contamination.

Real Event Displays

Another method for rapid assessment of network performance is to generate and evaluate the seismograms from moderate local and large teleseismic earthquakes recorded by the NHFN stations. This is an essential component of NHFN operations because the seismic data from local, regional, and teleseismic events are telemetered directly to the BSL and made available to the Northern California Seismic System (NCSS) real-time/automated processing stream for seismic response applications within a few seconds of being recorded by the NHFN.

Shown in Figure 4.3.3 is an example display of NHFN geophone and accelerometer channels for a recent local Bay Area earthquake (October 7, 2013 February 2013, *M*3.14 near Orinda, CA). It is apparent from this simple display that in general both the velocity and accelerometer channels are operating correctly, however, the channels SVIN.EP1, and SBRN.EP3 show excessive levels of noise that will need to be addressed. Stations CMSB, RB2B and OHLN were offline at the time, due to either landowner or construction related issues at those locations.

Figure 4.3.4 shows seismograms of the recent teleseismic M_w 8.2 earthquake off the northern coast of Chile (Lat.: 19.610S; Lon.: 70.760E; depth 25 km) occurring on April 1, 2014 23:46:47 (UTC). On this date and for this frequency band (0.1–0.5 Hz), network performance appears good for the vertical (DP1 and EP1) channels for nine of the stations in operation at the time. The RB2B.DP1, RFSB.DP1 and SVIN.EP1 channels have unacceptably high levels of noise that need to be addressed.

Signals from teleseismic events also serve as a good source for examining the relative polarities and responses of the BK borehole network station/components to seismic ground motion due to the near similar source-receiver paths after corrections are made for differences in instrument response among the stations. By rapidly generating such plots following large teleseismic events, quick assessment of the NHFN seismometer responses and polarities to real events is easily done and, if needed, corrective measures implemented with relatively little delay.

Both Figures 4.3.3 and 4.3.4 serve to illustrate the value of routine evaluation of both local (higher frequency) and teleseismic (lower frequency) events when monitoring the state of health of NHFN stations.

2013–2014 Activities

As in every year, routine maintenance, operations, quality control, and data collection play an important part in our activities. Other NHFN project activities have included: a) Specific station issues; b) efforts to obtain additional funds for future upgrade and expansion of the network; and c) Efforts to leverage NHFN activities through partnerships with various institutions outside of BSL

Specific Station Issues

BRIB: This year data collection from station BRIB has continued to be problematic. As with most NHFN sites, the BRIB installation is a complex integration of telemetry, power, recording, and sensor instrumentation. The BRIB station is particularly complex in that it collects coincident multi-component surface, borehole, broadband, short-period velocity and accelerometer data. Hence, getting at the root of the problems there has taken considerable effort with multiple site visits and contacts with the property administrators and power/telemetry providers. Considerable progress has been made for problems related to the power system at the site, and efforts to resolve several additional issues are continuing.

OHLN: The dense Bay Area population requires that most NHFN stations be cited on developed land, and permission to use the sites is at the discretion of generous private or public landowners. Consequently, landowner development of their properties sometimes requires temporary cessation and modifications to our station installations to accommodate both the landowners and our needs. This continues to be the case for station OHLN as it remains offline. However, notable progress has been made at modifying the power scheme at the site, and we expect OHLN to be back online soon.

W02B. Over the years, Caltrans has provided field and financial support for the operation and maintenance of this and several additional stations in the NHFN. However, this support has now been stymied by disputes over data propriety between Caltrans and U.C. Berkeley at the administrative level The site is experiencing what appears to be a failure in the data acquisition system. It is also located on the western span of the Bay Bridge and access to the site is limited, requiring travel on Caltrans boats. Due to the absence of maintenance support for this previously Caltrans supported site, operation of the station has had to be suspended. The proprietary issues between Caltrans and U.C. Berkeley were not able to be worked out so it appears that the site will remain inaccessible on a long term basis. Hence, long overdue site maintenance and the installation of a badly needed new BASALT data logger are no longer planned.

CMSB. Operation of our site outside the Cal Memorial Stadium (CMSB) was interrupted in late 2010 due to retrofit work on the stadium. It was later discovered that the borehole was accidentally destroyed during landscaping following the retrofit work. Responsibility for the destruction was identified and funds recovered to drill a new borehole in the same area. Drilling was completed in September of 2013. We are now in the process of working with the U.C. administration to acquire funds for replacement of the sensors and cable that were also destroyed as part of the landscaping. Once these funds become available, we will purchase and install the seismic equipment in the borehole and initiate data collection from the new replacement site.

Additional Funding

Operation of this Bay Area borehole network is supported by the Advanced National Seismic System (ANSS) and in the past through a partnership with the California Department of Transportation (Caltrans). ANSS provides operations and maintenance (O&M) support for a fixed subset of nine operational stations that were initiated as part of previous projects in which the USGS was a participant. Caltrans has in the past provided field and financial support for development and O&M for the remaining stations that have been added to the network through Caltrans partnership grants. In the past, Caltrans also provided additional support for upgrade and expansion of the network, when possible.

Due to the state budget crisis in the late 2000s, Caltrans began reviewing and modifying its financial commitments and its accounting practices relating to its funding of external projects, such as the NHFN project. This severely complicated effort to receive previously approved NHFN funding from Caltrans, and it imposed many additional administrative roadblocks to acquiring additional Caltrans support. In June of 2010, our team held two meetings at Berkeley with our Caltrans contact and made a presentation at Caltrans in Sacramento to argue against O&M funding reductions and for further upgrade and expansion of the NHFN. These efforts resulted in a request by Caltrans for a proposal to install surface instruments at up to six of our borehole installations and to reactivate three currently mothballed NHFN sites. We submitted our proposal in September of 2010. Subsequently, a reduction in the Caltrans budget for external support resulted in a request from Caltrans for us to reduce the scope of the proposal we submitted. We promptly responded to this request and tentative approval was promised. Funding was held up for over a year, however, by bureaucratic concerns and issues of proprietary rights. Haggling over these issues between the University of California (reaching as high as the UC Office of the President) and Caltrans continued well into 2013 and the resolution was less than beneficial. Both sides have agreed that they cannot come to an agreement, and progress has come to a halt with approval for the proposed project being withdrawn by Caltrans.

This has put an end to any further work on improving and expanding the NHFN with Caltrans help. At this time, maintenance of previously supported Caltrans stations that are accessible without Caltrans assistance continues using some internal BSL funding, though at a greatly reduced effort. This is resulting in significantly longer downtime for failed stations and significantly degraded data. Eventually, if future support is not forthcoming, these sites will need to be closed. Sites such as W02B, where access through Caltrans is required, have had to have operations suspended due to system failure.

Partnerships

The NHFN is heavily leveraged through partnerships with various institutions, and we have continued to nurture and expand these relationships. Over the past year, we have continued our collaborative partnerships with the USGS, St. Mary's College, and the Cal Maritime Academy, as well as striven to renew collaboration with Caltrans. In addition, the BSL has continued to coordinate with Lawrence Berkeley National Laboratory (LBNL) in their project to develop an LBNL array of borehole stations that provide complementary coverage to the HFN.

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Under Peggy Hellweg's, Robert Nadeau's and Doug Dreger's general supervision, Doug Neuhauser, Taka'aki Taira, and the engineering team (Sarah Snyder, Joshua Miller, and John Friday) all contribute to the operation of the NHFN. Robert Nadeau and Taka'aki Taira prepared this NHFN operations section of the BSL Annual Report.

Support for the NHFN this year was provided by the USGS through the cooperative networks grant program (grant number G10AC00093). In previous years, Pat Hipley of Caltrans has been instrumental in the effort to continue to upgrade and expand the network. Larry Hutchings and William Foxall of LLNL have also been important collaborators on the project in past years.

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4 Parkfield Borehole Network (HRSN)

Introduction

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

Figure 4.4.1 shows the location of the network stations, their relationship to the San Andreas fault, sites of significance from previous and ongoing experiments using the HRSN, clusters of repeating earthquakes being monitored by the network, nonvolcanic tremors recorded by the network and located using envelope alignment arrival-times and a migrating grid search location method (*Uhrhammer et al.*, 2001), background seismicity occurring this year and the epicenters of the 1966 and 2004 *M*6 earthquakes that motivated much of the research. The HRSN has recorded exceptionally high-quality data, owing to its 13 closely-spaced three-component borehole sensors (generally emplaced in the extremely low attenuation and background noise environment at 200 to 300 m depth (Table 4.4.2, its high-frequency, wide bandwidth recordings (0-100 Hz; 250 sps), and its sensitivity to very low amplitude seismic signals (e.g., recording signals from micro-earthquakes and non-volcanic tremors with equivalent magnitudes below 0.0 M_L).

Several aspects of the Parkfield region make it ideal for the study of small earthquakes and nonvolcanic tremors and their relationship to tectonic processes and large earthquakes. These include the fact that the network spans the SAFOD (San Andreas Fault Observatory at Depth) experimental zone, the nucleation region of earlier repeating magnitude 6 events, a significant portion of the transition from locked to creeping behavior on the San Andreas fault, the availability of three-dimensional P and S velocity models (*Michelini and McEvilly*, 1991; *Thurber et al.*, 2006), a long-term HRSN repeating seismicity catalog (complete to very low magnitudes and that includes over half of the M6 seismic cycle), a well-defined and relatively simple fault segment, the existence of deep nonvolcanic tremor (NVT) activity, and a relatively homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip).

In recent years, these features have also spurred additional investment in seismic instrumentation in the area that greatly enhances the HRSN's utility, including the ongoing installation of the TremorScope array (funded by the Moore foundation) and NFS's EarthScope SAFOD and PBO stations.

In a series of journal articles and Ph.D. theses, the cumulative, often unexpected, results of research by UC Berkeley and others using HRSN data trace the evolution of a new and exciting picture of the San Andreas fault zone, and they are forcing new thinking on the dynamic processes and conditions within both the seismogenic (upper ~15 km depths) and sub-seismogenic layers (~15-35 km depths), where recently discovered nonvolcanic tremors are occurring.

Parkfield has also become the focus of a major component of NSF's EarthScope project known as the San Andreas Fault Observatory at Depth (SAFOD) (http://www.earthscope.org/observatories/safod). The SAFOD project is a comprehensive effort whose objectives include drilling into the hypocentral zone of repeating M ~2 earthquakes on the San Andreas Fault at a depth of about 3 km and establishing a multi-stage geophysical observatory in the immediate proximity of these events. The purpose of such an observatory is to carry out a comprehensive suite of down-hole measurements in order to study the physical and chemical conditions under which earthquakes nucleate and rupture (*Hickman et al.*, 2004). In these efforts, the HRSN plays a vital support role by recording seismic data used to directly constrain seismic signals recorded in the SAFOD main hole and by recording seismic events in the surrounding region to provide information on the larger scale fault zone processes that give rise to any changes observed in the main hole.

HRSN Overview

Installation of the HRSN deep borehole sensors (200-300 m) initiated in late 1986, and recording of triggered 500 sps earthquake data began in 1987. The HRSN sensors are three-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. The sensors are also cemented permanently in place, ensuring maximum repeatability of the sensors' responses to identical sources, and allowing for precise relative measurements with minimal need for corrections and assumptions associated with moving the sensors. Originally a 10-station network, fully operational by January 1988, the HRSN was expanded to 13 borehole stations in late July 2001, and the original recording systems (see previous BSL Annual Reports) were upgraded to 24-bit acquisition (Quanterra 730s) and 56K frame relay telemetry to UCB. \ As part of funding from the American Recovery and Reinvestment Act (ARRA), an additional replacement/upgrade of the Quanterra 730 acquisition systems to 24-bit BASALT acquisition systems was accomplished in 2010–2011 and allows for local site storage and later retrieval of data during periods of sporadic telemetry failures. Properties of the sensors are summarized in Table 4.4.3.

The three newest borehole stations (CCRB, LCCB, and SCYB) were added, with NSF support, at the northwest end of the network as part of the SAFOD project to improve resolution of the structure, kinematics, and monitoring capabilities in the SAFOD drill-path and target zones. Figure 4.4.1 illustrates the location of the drill site, as well as locations of repeating earthquakes and nonvolcanic tremors recorded by the HRSN.

The three new stations have a similar configuration to the original upgraded 10 station network and include an additional channel for electrical signals. Station descriptions and instrument properties are summarized in Tables 4.4.2 and 4.4.3. All the HRSN data loggers employ FIR filters and extract data at 250 Hz (causal) and 20 Hz (acausal) (Table 4.4.1).

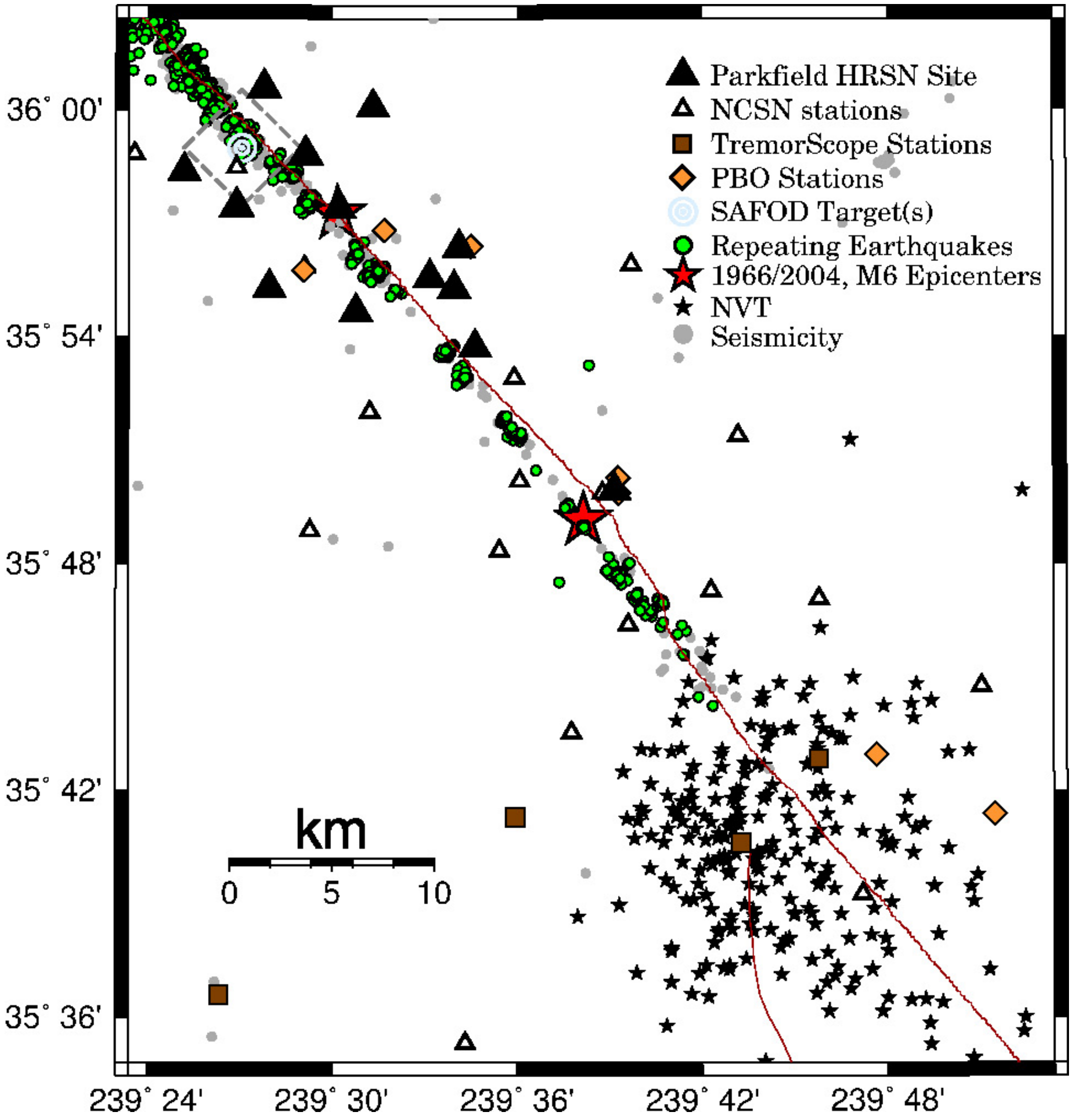

Figure 4.4.1: Map showing the San Andreas Fault trace and locations of the 13 Parkfield HRSN stations. Also shown are the 3 ~M2 SAFOD repeating earthquake targets (a 4 km by 4 km dashed box surrounds the SAFOD target zone), the epicenters of the 1966 and 2004 M6 Parkfield mainshocks, the locations (stars) of nonvolcanic tremors in the Cholame, CA area, and double-difference relocations of background (grey) and repeating (green) earthquakes processed by the integrated HRSN and NCSN networks. Recently installed or planned (Moore Foundation funded) TremorScope and borehole PBO stations (squares and diamonds, respectively) also complement the HRSN borehole coverage and are particularly useful for the study of the tremor. There are an additional five TremorScope and one PBO station outside the map bounds.

The remoteness of the SAFOD drill site and supporting HRSN stations required an installation of an intermediate data collection point at Gastro Peak, with a microwave link to our CDF (California Department of Forestry) facility. There was also one station, RMNB, that was located on Gastro Peak that transmitted directly to the CDF and served as a repeater for station LCCB. Prior to June 2008, eight of the HRSN sites transmitted either directly to or through repeaters directly to the CDF. This included stations RMNB and LCCB. The other five sites transmitted to a router at Gastro Peak, where the data was aggregated and transmitted to the CDF. However, due to disproportionately increasing landowner fees for access to the Gastro Peak site, we reduced our dependence on that site in the summer and fall of 2008 (in cooperation with the USGS) by re-routing telemetry of five of the sites previously telemetered through Gastro Peak to an alternative site at Hogs Canyon (HOGS). This eliminated the Gastro Peak microwave link, but left station RMNB and its repeater for LCCB at the mercy/good-graces of the Gastro Peak landowner. Subsequent negotiations with the landowner stalled and it was decided that RMNB was to be closed. An alternative repeater path for LCCB was also identified and made operational.

Continuous 20 and 250 Hz data from all HRSN channels are recorded and telemetered to the USGS site at Carr Hill for automatic picking and inclusion into Northern California Seismic System (NCSS) processing. The waveform data are also telemetered over a dedicated T1 circuit to the USGS and the Northern California Earthquake Data Center (NCEDC) at UC Berkeley

Sensor	Channel	Rate (sps)	Mode	FIR
Geophone	DP?	250.0	C	CA
Geophone	BP?	20.0	C	Ac

Table 5.4.1: Data streams currently being acquired at operational HRSN sites. Sensor type, channel name, sampling rate, sampling mode, and type of FIR filter are given. C indicates continuous; Ac acausal; Ca causal. "?" indicates orthogonal, vertical, and two horizontal components.

for archiving and for online access by the community. The HRSN system also generates autonomous station triggers and event associations that are also archived at the NCEDC.

The HRSN's telemetry system provides remote access to the local site data acquisition systems for state of health monitoring and control, and the recent upgrade to BASALT acquisition systems allows for local storage and retrieval of the data during telemetry outages.

Another feature of the HRSN system that has been particularly useful both for routine maintenance and for pathology identification has been the Internet connectivity of the central site processing computer and the individual stations' data acquisition systems. Through this connectivity, locally generated warning messages from the central site processor are sent directly to the BSL for evaluation by project personnel. If, upon these evaluations, more detailed information on the HRSN's performance is required, additional information can also be remotely accessed from the central site processing computer and generally from the individual site data loggers as well. Analysis of this remotely acquired information has been useful for trouble shooting by allowing field personnel to schedule and plan the details of maintenance visits to Parkfield. The connectivity also allows for local site acquisition shutdowns and restarts and for remote implementation of data acquisition parameter changes when needed.

The network connectivity and seamless data flow to UC Berkeley also provide near-real-time monitoring capabilities that are useful for rapid evaluation of significant events as well as the network's general state of health.

For example, shown in Figure 5.4.2 are surface wave seismograms of the teleseismic M_w 8.2 earthquake off the northern coast of Chile (Lat.: 19.610S; Lon.: 70.760E; depth 25 km) occurring on April 1, 2014 23:46:47 (UTC) recorded on the SP1 (vertical) channels of the 12 HRSN borehole stations in operation at the time. Station RMNB no longer records data due to landowner issues. The seismic data from the quake was telemetered to Berkeley and available for analysis by the Northern California Seismic System (NCSS) real-time/automated processing stream within a few seconds of being recorded by the HRSN.

This is also a good signal source for examining the relative responses of the BP borehole network station/components to seismic ground motion. In this case, the vertical channels for 10 of the 12 stations in the 0.1-0.5 Hz band appeared to be working well and with the proper polarities at the time of the earthquake. However, the vertical channel for FROB shows an anomaly, and it appears that the vertical channel for VARB did not recorded any signal from the earthquake. By rapidly generating such plots following large teleseismic events, quick assessment of the HRSN seismometer responses to real events is easily done and corrective measures implemented with relatively little delay.

Data Flow

Initial Processing Scheme

Continuous data streams on all HRSN components are recorded at 20 and 250 sps on disk locally on the BASALT data-logger systems and transmitted in near-real-time over the T1 circuit to the USGS at Menlo Park, CA, where they are integrated into the Northern California Seismic System (NCSS) real-time/automated processing stream. The data is also transmitted to the Berkeley Seismological Laboratory (BSL) for archiving at the NCEDC. This integration of HRSN data into the NCSS data flow has significantly increased the sensitivity of the NCSN catalog at lower magnitudes, effectively doubling the number of small earthquake detections in the Parkfield area and SAFOD zone.

Shortly after being collected and recorded to disk on the central site HRSN computer at the USGS Carr Hill facility, event triggers for the individual stations are determined, and a multi-station trigger association routine then processes the station triggers and generates a list of HRSN-specific potential earthquakes.

For each potential earthquake association, a unique event identification number (compatible with the NCEDC classification scheme) is also assigned. Prior to the San Simeon earthquake of December 22, 2003, 30 second waveform segments were then collected for all stations and components and saved to local disk as an event gather, and event gathers were then periodically telemetered to BSL and included directly into the NCEDC earthquake database (DBMS) for analysis and processing.

Because of its mandate to record very low amplitude seismic signals and microearthquakes in the Parkfield area, the HRSN was designed to operate at very high gain levels to enhance signal sensitivity. This comes at the expense of dynamic range for the larger events (above ~M3.0). The sensitivity to low amplitude signals is also enhanced by the placement of sensors in the low noise borehole environment (200-300 m depth) and by exhaustive efforts at knocking down extraneous noise sources that arise in each station's electronics, grounding, power, and telemetry systems and from interference from anthropogenic noise sources near the stations. As a consequence of the network's high sensitivity, the HRSN also records numerous outside signals from regional events and relatively distant and small amplitude nonvolcanic tremor events. For example, spot checks of aftershocks following the M 6.5 San Simeon earthquake of December 22, 2003 using continuous data and HRSN event detection listings revealed that the overwhelming majority of HRSN generated detec-

Site	Net	Latitude	Longitude	Surf. (m)	Depth (m)	Date	Location
EADB	BP	35.89525	-120.42286	466	245	01/1987 -	Eade Ranch
FROB	BP	35.91078	-120.48722	509	284	01/1987 -	Froelich Ranch
GHIB	BP	35.83236	-120.34774	400	63	01/1987 -	Gold Hill
JCNB	BP	35.93911	-120.43083	527	224	01/1987 - 02/18/2008	Joaquin Canyon North
JCNB*	BP	35.93911	-120.43083	527	4	07/2011 -	Joaquin Canyon North
JCSB	BP	35.9212	-120.43408	455	155	01/1987 -	Joaquin Canyon South
MMNB	BP	35.95654	-120.49586	698	221	01/1987 -	Middle Mountain
RMNB*	BP	36.00086	-120.47772	1165	73	01/1987 - 07/20/2011	Gastro Peak
SMNB	BP	35.97292	-120.58009	699	282	01/1987 -	Stockdale Mountain
VARB	BP	35.92614	-120.44707	478	572	01/1987 - 08/19/2003	Varian Well
VARB*	BP	35.92614	-120.44707	478	298	08/25/2003 -	Varian Well
VCAB	BP	35.92177	-120.53424	758	200	01/1987 -	Vineyard Canyon
CCRB	BP	35.95718	-120.55158	595	251	05/2001 -	Cholame Creek
LCCB	BP	35.98005	-120.51424	640	252	08/2001 -	Little Cholame Creek
SCYB	wBP	36.00938	-120.5366	945	252	08/2001 -	Stone Canyon

Table 5.4.2: Stations of the Parkfield HRSN. Each HRSN station is listed with its station code, network id, location, operation period, 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 is also given. Coordinates and station names for the three new SAFOD sites are given at the bottom. Notes, denoted with '*': There are 2 entries for JCNB, which failed in February of 2008 and has been replaced with a post-hole installation with ARRA funds. There are 2 entries for VARB, whose recording from a deep failed sensor (failure in August, 2003) was changed to a shallower sensor. Recording of data from station RMNB ended in July of 2011, due to landowner issues.

tions following San Simeon resulted from seismic signals generated by San Simeon's aftershocks, despite the HRSN's ~50 km distance from the events. Data from the California Integrated Seismic Network (CISN) show that there were ~1,150 San Simeon aftershocks with magnitudes >1.8 in the week following San Simeon, and during this same period, the number of HRSN event detections was ~10,500 (compared to an average weekly rate before San Simeon of 115 HRSN detections). This suggests that the HRSN was detecting San Simeon aftershocks well below magnitude 1 at distance of ~50 km or more.

Current Processing

Since the beginning of the network's data collection in 1987, and up until 2002, local and regional events were discriminated based on analyst assessment of S-P times, and only local events with S-P times less than ~2.5 s at the first arriving station were picked and located as part of the HRSN routine catalog. However, because of the network's extreme sensitivity to the large swarm of aftershocks from the 2003 San Simeon and 2004 Parkfield *M*6 earthquakes (e.g., in the first five months following the San Simeon mainshock, over 70,000 event detections were made by the HRSN system, compared to an average five month detection rate of 2500 prior to San Simeon) and because of ever declining funding levels, analyst review of individual microearthquakes was abandoned.

In addition, the dramatic increase in event detections following the San Simeon and Parkfield earthquakes vastly exceeded the HRSN's capacity to process and telemeter both continuous and triggered event waveform data. To prevent the loss of seismic waveform coverage, processing of the triggered waveform data was discontinued to allow the telemetry and archival of the 20 and 250 sps continuous data to continue uninterrupted. Subsequent funding limitations have since precluded reactivation of the triggered event processing. Cataloging of associated event triggers from the modified REDI real-time system algorithm continues, however, and both the continuous waveform data and trigger times are telemetered to and archived at the NCEDC, for access by the research community.

Because funding to generate catalogs of local micro-events from the tens of thousands of San Simeon and Parkfield aftershocks was not forthcoming, major changes in our approach to cataloging events had to be implemented. For example, HRSN data flow has now been integrated into the NCSS automated event detection, picking, and catalog processing. In addition, we have implemented a high resolution cross-correlation (pattern matching) based procedure to automatically detect, pick, locate, double-difference relocate, and determine magnitudes for select similar and repeating earthquake families down to very low magnitudes (i.e., below -0.0M_L). These new schemes are discussed in more detail in the activities section below under subsection "SOH using Similar and Repeating Events".

Site	Sensor	Z	H1	H2	RefTek 24	Quanterra 730	BASALT
EADB	Mark Products L22	-90	170	260	01/1987 - 06/1998	03/2001 - 07/2011	07/2011 -
FROB	Mark Products L22	-90	338	248	01/1987 - 06/1998	03/2001 - 11/2010	11/2010 -
GHIB	Mark Products L22	90	failed	unk	01/1987 - 06/1998	03/2001 - 07/2011	07/2011 -
JCNB	Mark Products L22	-90	0	270	01/1987 - 06/1998	03/2001 - 02/2008	-
JCNB*	Oyo GeoSpace GS-20DX	90	0	90	-	-	09/2011 -
JCSB	Geospace HS1	90	300	210	01/1987 - 06/1998	03/2001 - 04/2011	04/2011 -
MMNB	Mark Products L22	-90	175	265	01/1987 - 06/1998	03/2001 - 12/2010	12/2010 -
RMNB*	Mark Products L22	-90	310	40	01/1987 - 06/1998	03/2001 - 07/2011	-
SMNB	Mark Products L22	-90	120	210	01/1987 - 06/1998	03/2001 - 04/2011	04/2011 -
VARB	Litton 1023	90	15	285	01/1987 - 06/1998	03/2001 - 04/2011	-
VARB*	Litton 1023	90	358	88	01/1987 - 06/1998	03/2001 - 04/2011	04/2011 -
VCAB	Mark Products L22	-90	200	290	01/1987 - 06/1998	03/2001 - 04/2011	04/2011 -
CCRB	Mark Products L22	-90	258	348	-	05/2001 - 08/2011	08/2011 -
LCCB	Mark Products L22	-90	50	140	-	08/2001 - 09/2011	09/2011 -
SCYB	Mark Products L22	-90	342	72	-	08/2001 - 08/2011	08/2011 -

Table 5.4.3: Instrumentation of the Parkfield HRSN. Most HRSN sites have L22 sensors and were originally digitized with a RefTek 24 system. The WESCOMP recording system failed in mid-1998, and after an approximate three year hiatus the network was upgraded and recording was replaced with a new 4-channel system. The new system, recording since July 27, 2001, uses a Quanterra 730 4-channel acquisition. Three new stations were also added during the network upgrade period (bottom) In 2010-2011, with ARRA funding, additional replacement/upgrade to 24-bit BASALT acquisition with station-local data storage took place. Notes, denoted with '*': There are 2 entries for JCNB, which failed in February of 2008 and has replaced with a post-hole installation with ARRA funds. There are 2 entries for VARB, whose recording from a deep failed sensor (failure in August, 2003) was changed to a shallower sensor. Recording of data from station RMNB ended in July of 2011, due to landowner issues.

2013–2014 Activities

In addition to routine operations and maintenance, project activities this year include: a) Presentation to the National Earthquake Prediction Evaluation Council (NEPEC) on the state of research and monitoring at Parkfield using the HRSN, b) Further development and implementation of HRSN state of health (SOH) monitoring using repeating events, c) Routine monitoring of non-volcanic tremor activity in the Parkfield-Cholame area and routine updates of the web-page on tremor activity in support of the TremorScope project, and d) Continued support of SAFOD activities with updates of the repeating and similar event seismicity catalog.

Routine Operations and Maintenance

Routine maintenance tasks required this year to keep the HRSN in operation include replacement of aging with new preamplifier units and testing/confirmation of the new design's performance, cleaning and replacing corroded electrical connections, grounding adjustments, cleaning solar panels, testing and replacing failing batteries, ventilating battery and data logger housings to address problems with low power during hot weather, and repairing and realigning repeater sites and antennas.

Remote monitoring of the network's health using the Berkeley Seismological Laboratory's internally developed tools and SeisNetWatch software is also performed to identify both problems that can be resolved over the Internet (e.g., rebooting of data acquisition systems due to clock lockups) and more serious problems requiring field visits. Over the years, such efforts have paid off handsomely by providing exceptionally low noise recordings of low amplitude seismic signals produced by microearthquakes (below 0.0M_L) and nonvolcanic tremors.

The network connectivity over the T1 circuit also allows remote monitoring of various measures of the state of health (SOH) of the network in near-real-time using waveforms directly. For example, background noise levels can be rapidly evaluated. We have developed and implemented an automated estimation of the power spectral density (PSD) distributions of background noise for all recorded HRSN channels and have developed summary PSD plots of these estimations to promote rapid evaluation of the noise levels through time.

Shown in Figure 5.4.3 are power spectral density (PSD) plots of background noise for the 12 vertical HRSN channels in operation during 2013 for the 2-8 Hz frequency band where strong tremor signals are typically recorded. Continuous automated updating of such data plots in a variety of bands allow BSL personnel to rapidly evaluate changes in the network's station response to seismic signals across the wide band high frequency spectrum of the borehole HRSN sensors. Changes in the responses often indicate problems with

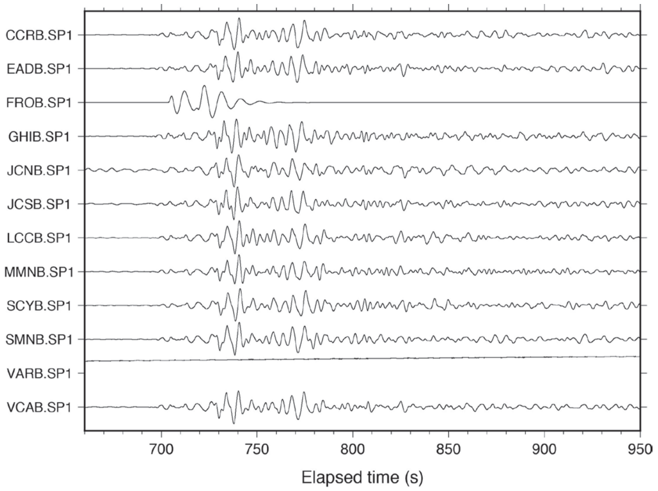

Figure 5.4.2: Plot of surface wave seismograms of the teleseismic Mw 8.2 earthquake off the northern coast of Chile (Lat.: 19.610S; Lon.: 70.760E; depth 25 km) occurring on April 1, 2014 23:46:47 (UTC) recorded on the SP1 (vertical) channels of the 12 HRSN borehole stations in operation at the time. Here, vertical component geophone (velocity) data have been 0.1-0.5 Hz bandpass filtered and normalized by the maximum amplitude for each trace.

the power, telemetry, or acquisition systems, or with changing conditions in the vicinity of station installations that are adversely affecting the quality of the recorded seismograms. Once state of health issues are identified, further remote tests can be made to more specifically determine probable causes, and corrective measures are then planned in advance of field deployment within a relatively short period of time.

Presentation to NEPEC

In a cost cutting effort, the USGS asked the National Earthquake Prediction Evaluation Council (NEPEC) this year to review the state of research and monitoring work around Parkfield, and to provide recommendations for future priorities. Roland Bürgmann and Robert Nadeau of the BSL were asked to attend the meeting, to provide a briefing on research and monitoring efforts in the area using HRSN data, to listen to other presentations on Parkfield area research and monitoring efforts, and to share in discussions on the relative importance and future possibilities of the various data collection and analysis efforts taking place in the area. While it was worrisome that this discussion, prompted by squeezed budgets within the USGS EHP program was even needed, the case for continued support for HRSN operations was relatively easy to make and a number of positive comments were made about the HRSN by the NEPEC members (e.g., "The HRSN has come out very high on the priority list" and "If anything ought to stay, it is the HRSN".). It seems likely, therefore, that funding for continued HRSN operations will survive this round of USGS budget prioritization.

SOH using Similar and Repeating Events

The increased microseismicity (thousands of events) resulting from the San Simeon M6.5 (SS) and Parkfield M6 (PF) events, the lack of funds available to process and catalog the increased number of microearthquakes, and the increased interest in using the microquakes in repeating earthquake and SAFOD research have required new thinking on how to detect and catalog microearthquakes recorded by the HRSN.

One action taken to help address this problem has been to integrate HRSN data streams into the NCSN event detection and automated cataloging process. This approach has been successful at detecting and locating a significantly greater number of microearthquakes over the previous NCSN detection and location rate, essentially doubling the number of events processed by the NCSN. However, the HRSN-sensitized NCSN catalog is still only catching about half the number of local events previously cataloged by the HRSN using the old, HRSN-centric processing approach. Furthermore, triggered waveforms for the additional small NCSN-processed events are often not reviewed by an analyst, nor do these smaller events often have NCSN magnitude determinations associated with them.

These limitations can severely hamper research efforts relying on the more numerous similar and characteristically repeating microevents (*e.g.*, earthquake scaling studies, SAFOD related research, deep fault slip rate estimation, and the compilation of recurrence interval statistics for time-dependent earthquake forecast models). They also reduce the efficacy of using frequently recurring microevents as a tool for monitoring the network state-of-health (SOH).

To help overcome these limitations, we continued this year to implement our semi-automated similar-event cataloging scheme based on pattern matching (match filter) scans using cross-correlation of the continuous HRSN data. The method uses a library of reference event (pattern) waveforms, picks, locations, and magnitudes that have been accurately determined, to automatically detect, pick, locate, and determine magnitudes for events similar to the reference event with a level of accuracy and precision that only relative event analysis can bring.

The similar event detection is also remarkably insensitive to the magnitude of the reference event used, allowing similar microevents ranging over about three magnitude units to be fully cataloged using a single reference event, and it does a remarkably good job at discriminating and fully processing multiple superposed events.

Once a cluster of similar events has been processed, an additional level of resolution can then be achieved through the identification and classification of the subset of characteristically repeating microearthquakes (*i.e.*, near identical earthquakes) occurring within the similar event family (Figure 5.4.4). The pattern scanning approach also ensures optimal completeness of repeating sequences owing to scans of the matching pattern through "all" available continuous data, which is critical for applications relying on recurrence interval information. For example, only about half of the magnitude 0.26 events shown in Figure 5.4.4 were picked up by the NCSN-HRSN integrated network.

Figure 5.4.4 also shows how stable the performance of channel DP1 on the borehole VCAB.BP has remained over the ~five year period shown. Due to station malfunctions or

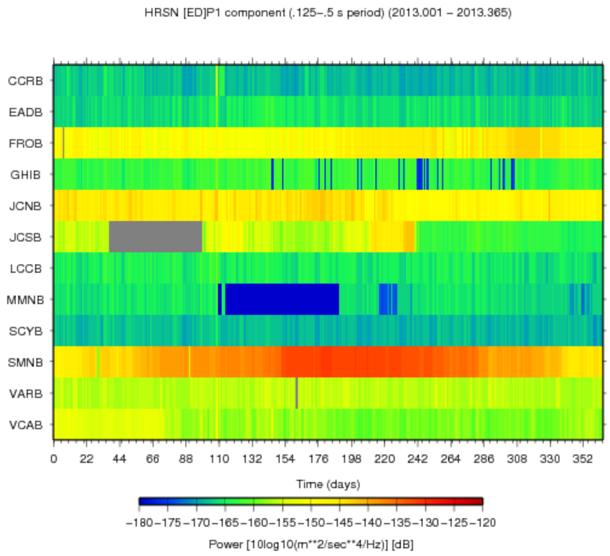

Figure 5.4.3: 2013 summary plots of 250 sps vertical component (i.e., DP1 channel) background noise Power Spectral Density (PSD) levels for the 12 operating HRSN borehole stations in the strong tremor frequency band (2-8 Hz or period 0.125–.5 s). The mean PSD (dB) ranking (lowest to highest) at 3 Hz obtained from all available 2013 data on these channles are:

MMNB.BP.DP1	-166.636
SCYB.BP.DP1	-163.456
CCRB.BP.DP1	-161.935
LCCB.BP.DP1	-159.035
EADB.BP.DP1	-156.827
GHIB.BP.DP1	-154.757
JCSB.BP.DP1	-151.567
VCAB.BP.DP1	-150.041
VARB.BP.DP1	-149.134
FROB.BP.DP1	-141.947
JCNB.BP.DP1	-139.245
SMNB.BP.DP1	-136.973

Note that failed station JCNB (failure in late 2007) has been reopened as a post-hole installation. The blue period for station MMNB between ~days 110 and 180 reflects a malfunction eventually found to be occuring in the aging pre-amplifier unit. The new pre-amplifier replacement was tested at MMNB first and eventually fixed the problem.

human error during field maintenance, this would not necessarily have been the case. Because repeating events can generally be reliably identified using any combination of 4 of the HRSN's 35 channels, assessment of the channel responses for channels not in the 4 channel combination can be carried out. This can be carried out repeatedly through time as additional repeats are identified with time resolutions depending on the number of repeating sequences used and the frequency of their repeats. Repeating sequences of this magnitude typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences. Hence, on average, evaluations of this type can be possible approximately every 10 days on an automated basis. However, there are on the order of 200 such sequences known in the Parkfield area, and if one is willing to include even more frequently occurring similar but non-identical events into the equation, near-daily automated SOH analyses are a possibility.

Armed with this type of information, technicians and field engineers can quickly identify and address major problems. In addition to a visual assessment, the high similarity of the events lends itself to the application of differencing techniques in the time and frequency domains to automatically identify even subtle SOH issues. For other networks recording continuously in the Parkfield area (e.g., NCSN, BDSN/TremorScope) it is also a relatively simple process to extend the SOH analysis using characteristic repeating event signals recorded at their stations (See BDSN station RAMR example in Figure 5.4.5 of the BSL's 2011–2012) annual report. Furthermore, numerous repeating and similar event sequences are also known to exist in the San Francisco Bay, San Juan Bautista and Mendocino Triple Junction areas, where continuous recording takes place. Hence, application of the repeating event SOH technique to these zones should also be feasible.

This year we have finished adapting our cataloging codes to take advantage of faster computing now available on LINUX based machines. We have expanded the library of reference event patterns and retroactively scanned these patterns through previously recorded and ongoing data to capture and catalog an ever growing body of similar and repeating earthquakes for research purposes, in support of SAFOD, and for SOH monitoring (including the use of repeaters to identify and correct problems associated with the recently activated TremorScope stations). We have also continued to revise and automate our SOH waveform displays for rapid evaluation of HRSN performance based on repeater waveforms and have begun development of additional automated processing and display schemes to include visualization of spectral characteristics to the repeating event SOH analyses.

Tremor Monitoring and TremorScope

The HRSN played an essential role in the initial discovery of nonvolcanic tremors (NVT) and associated Low Frequency Events (LFE) along the San Andreas Fault (SAF) below Cholame, CA (*Nadeau and Dolenc*, 2005; *Shelly et al.*, 2009), and continues to play a vital role in ongoing NVT and LFE research. The Cholame tremors occupy a critical location between the smaller Parkfield (~*M*6) rupture zone and the adjacent and much larger Ft. Tejon (~*M*8) rupture zone along the SAF to the southeast (Figure 5.4.1). Because the time-varying nature of tremor activity is believed to reflect time-varying deep deformation and presumably episodes of accelerated stressing of faults (*Guilhem and Nadeau*, 2012), and because anomalous changes in Cholame area NVT activity preceded the 2004 Parkfield *M*6 earthquake (*Nadeau and Guilhem*, 2009; *Shelly*, 2009), and because tremor activity appears to be an ongoing process in the area (*Guilhem and Nadeau*, 2012) we are continuing to monitor the tremor activity observable by the HRSN to look for additional anomalous behavior that may signal an increased likelihood of another large SAF event in the region.

To date, over 3200 NVT bursts have been identified and

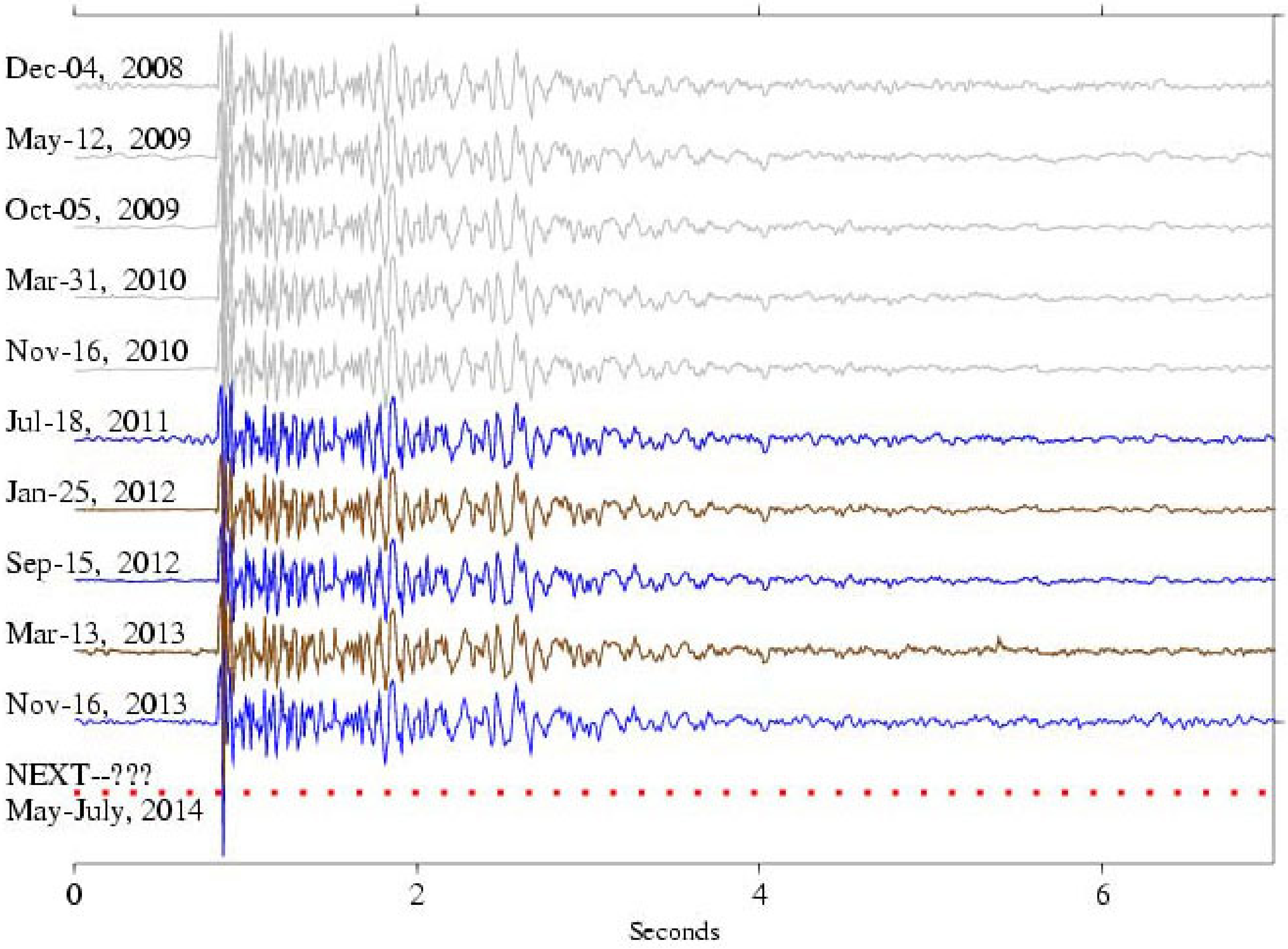

Figure 5.4.4: The ten most recent repeats of a characteristic sequence of repeating magnitude 0.26 (M_p, USGS preferred magnitude) microearthquakes recorded by vertical (DP1) channel of HRSN station VCAB. This sequence has repeated 50 times since the initiation of HRSN recording in 1987. Characteristically repeating microevents are extremely similar in waveform (typically 0.95 cross-correlation or better). High-precision relative location and magnitude estimates of these events show they are also nearly collocated (to within 5-10 m) and have essentially the same magnitude (+/- 0.13 M_p units, among all sequences studied). Immediately following the Parkfield *M*6 mainshock on Sept. 28, 2004, the frequency of repetition was greatly accelerated due to post-seismic loading from the main-shock (e.g., seven repeats in the three months following the mainshock). As time passes, however, the post-seismic effects from the mainshock have gradually diminished, repeating about two times a year.

In the BSL annual reports for 2010–2011, 2011–2012 and 2012–2013 we noted that the recurrence intervals (i.e., times between events in the repeating sequence) for events in this sequence were on the order of six to eight months. Based on this we predicted in the 2010–2011 report that the next repeat of the sequence would take place sometime in May through July of 2011. The occurrence of the July 18, 2011 event (blue/black) proved our prediction to be correct, and a subsequent repeat on January 25, 2012 (brown/dark-gray) also followed the six to eight month recurrence pattern. Another prediction was made in the following 2011–2012 annual report where we predicted at least one and possibly two additional repeats within the next year, with the next repeat expected in July through September of 2012. These preditictions were also fulfilled with the occurrence of the September 15, 2012 (blue/black) and March 13, 2013 (brown/dark-gray) events. Again in the 2012–2013 annual report we predicted once again that at least one and possibly two more additional repeats would occur within the next year, with the next repeat expected in September through November of 2013. This preditiction was also fulfilled with the occurrence of the November 16, 2013 (blue/black) event. The dashed line labeled “NEXT” serves to illustrate our expectation that events in this sequences will continue the repeat pattern. Because the recent recurrence intervals continue to range between about six to eight months, we again predict at least one and possibly two additional repeats within the next year, with the next repeat expected to occur sometime in May through July of 2014. The most recent search period for repeats at at the time of this writing went through April 7 of 2014, with no subsequent repeat yet expected nor observed.

For network operational purposes, the repeating behavior of this and other sequences in the Parkfield area allows us to use repeating sequences to monitor changes in channel response relative to past performance and to rapidly identify and correct state-of-health (SOH) issues with real, naturally occurring signals. Making future predictions for such frequently repeating events and testing the prediction using real earthquakes could also be a useful motivating tool for teaching about earthquakes in an educational setting.

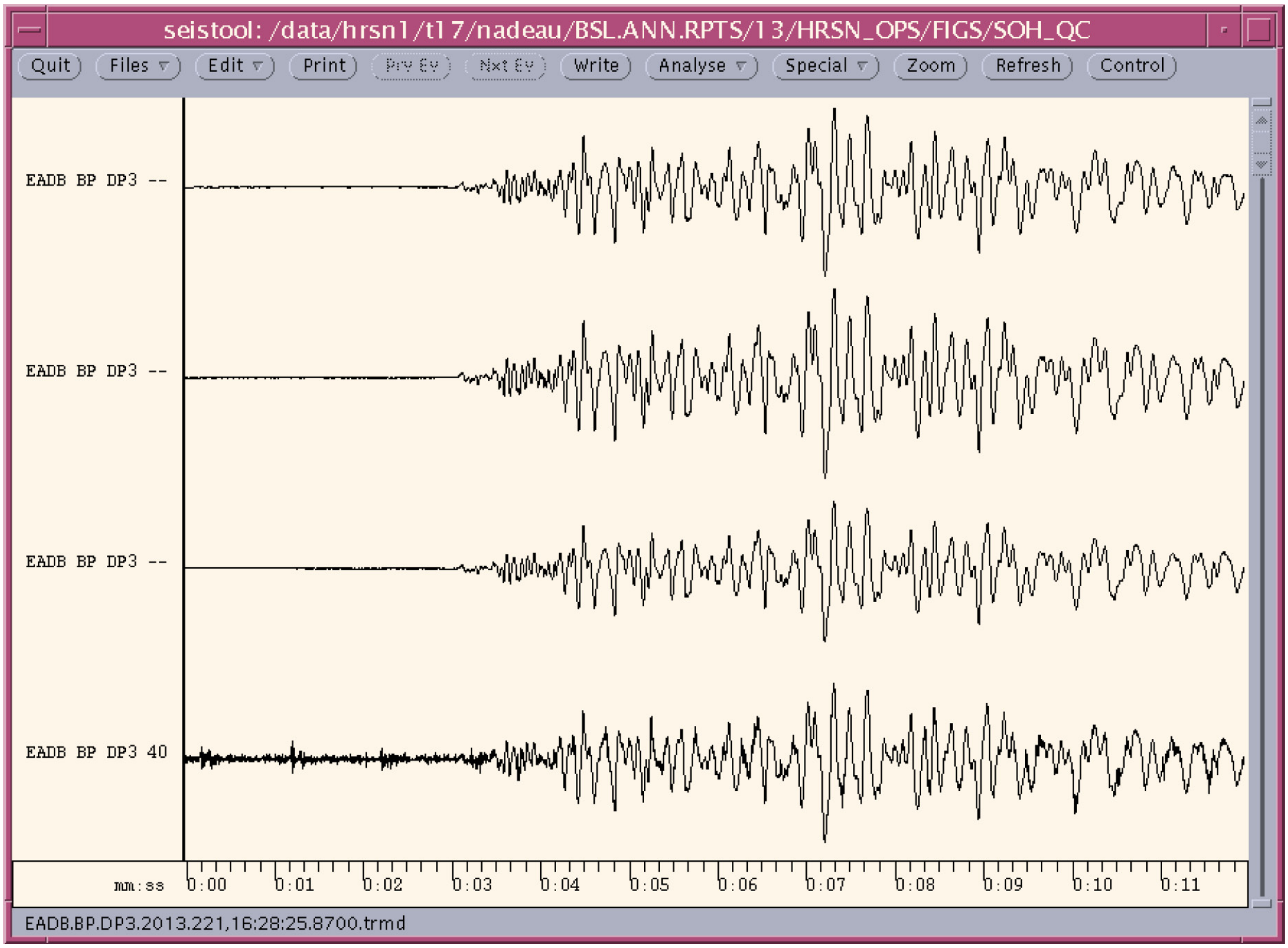

Figure 5.4.5: Repeating earthquake data illustrating their utility for identifying problematic channel responses. Here a repeat of EarthScope's SAFOD SF sequence (~M2.1) occurring on August 09, 2013 was identified using HRSN stations. The event and its previous repeats were used to evaluate the performance of stations from the HRSN and other networks out to distances greater than 50 km from the HRSN. Shown are the last four SF sequence events recorded on the DP3 horizontal channel of Berkeley's HRSN station EADB with no filtering. EADB is 16 km from the repeating events. From top to bottom, the events occurred on 11/02/2006, 12/20/2008, 11/23/2010, 05/30/2007, and 08/09/2013, respectively. Waveforms for the first three events are well recorded and consistent, indicating healthy station response. However, for the most recent event a significant degradation in response is seen. Signal from the 2013 event is contaminated with spiking about every second (indicative of soloar charger issues) and a background noise buzz with an ~ white spectrum is superposed on the earthquake signal. Corrective action taken was to ensure proper grounding of the electronic components at the installation and to replace the datalogger.

cataloged, and regular updates of the NVT catalog continue on an ~biweekly basis. Over the last year we have also developed a website displaying a map and section of recent 90-day tremor activity as well as a complete list of detected Parkfield-Cholame area tremor from July of 2001. This can be downloaded by researchers and the public at http://seismo.berkeley.edu/research/recent_tremor.html.

Efforts in Support of SAFOD

An intensive and ongoing effort by the EarthScope component called SAFOD (San Andreas Fault Observatory at Depth) was undertaken to drill through, sample, and monitor the active San Andreas Fault at seismogenic depths and in very close proximity (within a few tens of meters or less) to a repeating magnitude 2 earthquake site. The HRSN data play a key role in these efforts by providing azimuthal coverage of low noise and high sensitivity seismic waveforms from active and passive sources in the SAFOD region, by providing a backbone catalog of very small similar and repeating earthquakes detections, and by recording and archiving continuous waveform data.

As of early September 2007, SAFOD drilling had penetrated the fault near the HI repeating target sequence and collected core samples in the fault region that presumably creeps and surrounds the repeatedly rupturing HI patch. Unfortunately, due to complications during drilling, penetration and sampling of the fault patch involved in repeating rupture was not possible, though core sampling and installation of seismic instrumentation in the region adjacent to the repeating patch was achieved. Current efforts are focused on analysis of collected core samples and long-term monitoring of the ongoing chemical, physical, seismological, and deformational properties in the zone (in particular any signals associated with subsequent repeats of the SAFOD target sequences).

HRSN activities this year have contributed in three principal ways to these and longer-term SAFOD monitoring efforts:

1) Processing of integrated HRSN and USGS data streams in the Parkfield area continues, effectively doubling the number of small events available for monitoring seismicity in the SAFOD target zone and for constraining relative locations of the ongoing seismic activity.

2) Telemetry of all HRSN channels (both 20 and 250 sps data streams) continues to flow directly from Parkfield, through the USGS Parkfield T1 and the Northern California Earthquake Management Center (NCEMC) T1, to the USGS and the BSL for near real-time processing, catalog processing, and data archiving at the Web-accessible NCEDC portal. This also provides near-real-time access to the HRSN data for the SAFOD community, without the week- or month-long delay associated with the previous procedure of having to transport DLT tapes to Berkeley to upload and quality check the data.

3) Continued monitoring and expansion of our repeating (characteristic and similar event sequences) earthquake catalog, with particular focus on expansion and refinement of repeating event data within the 1.5 cubic km volume centered on the SAFOD target zone. In 2012–2013, we expanded the number of repeating sequence reference patterns in this zone from 3 to 18 and cataloged (detected, double-difference relocated, and determined magnitudes for) repeating and similar events associated with these sequences. This year we have continued to update the sequences with ongoing similar and repeated events, resulting in an expansion of the number of earthquakes within this small SAFOD focused volume to over 1,300 unique microquakes. The pattern matching approach to detection is prone to identifying the same event from more than one reference earthquake, so a procedure was also developed to remove redundant events from the overall catalog. A procedure was also developed to integrate arrival time information from the redundant pattern matches to improve connectivity of events from different similar event sequences in the double-difference relocations.

Continued monitoring of the 18 sequences in the immediate SAFOD zone this year has also led to the identification of the next repeats of the SAFOD SF and LA sequences which both occurred on August 09, 2013. The apparent triggering within less than a day of the repeat of the LA sequence by the repeat of the SF sequence reflects the first evidence of a return of this triggering relationship since its disruption at the time of the 2004 Parkfield *M*6 mainshock.

Figure 5.4.5 shows recordings of the horizontal (DP3) channel from HRSN station EADB for the most recent (bottom) and three previous repeats of the SAFOD SF sequence. While the repeated nature of these events is clearly apparent in the waveforms, it is also clear that the quality of the recording of the most recent event is below standard. Waveforms recorded on most other HRSN channels do not show the high frequency lower amplitude buzz and spiking apparent on the EADB DP3 channel. Replacement of the old preamp with the new preamp design in the spring of 2014 has rectified the problem. While degradation of the signal is apparent visually, such degradation is not generally apparent from automated quality control checks of station performance. This illustrates, then, the additional benefit of visual inspection and comparison of repeating events in SOH evaluations.

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Under Peggy Hellweg's and Robert Nadeau's general supervision, Doug Neuhauser, Taka'aki Taira, and the engineering team (Joshua Miller, Sarah Snyder and John Friday) all contribute to the operation of the HRSN. Robert Nadeau prepared this section with help from Taka'aki Taira. During this reporting period, operation, maintenance, and data processing for the HRSN project was supported by the USGS, through grant G10AC00093.

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5 Data Acquisition and Quality Control

Introduction

Stations from the networks operated by the BSL transmit data continuously to the BSL facilities on the UC Berkeley campus for analysis and archiving. In this section, we describe activities and facilities which pertain to the individual networks described in Operational Sections 4.1, 4.3, and 4.4, including procedures for data acquisition and quality control, and sensor testing capabilities and procedures. Some of these activities are continuous from year to year and have been described in prior BSL annual reports. In this section, we describe changes and activities which are specific to 2013–2014.

Data Acquisition Facilities

The data acquisition computers and associated telemetry equipment are located in the campus computer facility in Warren Hall at 2195 Hearst Avenue. This building was constructed according to current "emergency grade" seismic codes and is expected to be operational even after a $M7$ earthquake on the nearby Hayward Fault. The hardened campus computer facility within was designed with special attention for post-earthquake operations. The computer center contains state-of-the art seismic bracing, UPS power and air conditioning with generator backup, and extensive security and equipment monitoring.

Data Acquisition

Central-site data acquisition for data from the BDSN/HRSN/NHFN/mPBO networks is performed by two computer systems in the Warren Hall data center (Figure 4.5.1). These acquisition systems also collect data from the Parkfield-Hollister electromagnetic array and the BARD network. A third system is used primarily for data exchange. It transmits data to the U.S. National Seismograph Network (USNSN) from HOPS, CMB, SAO, WDC, HUMO, JCC, MOD, MCCM, ORV and YBH. Data from various subsets of stations also go to the Pacific and Alaska Tsunami Warning Centers, to the University of Washington and to the University of Reno, Nevada. In addition, the Southern California Earthquake Management Center has access to our wavepools for retrieving waveform data to include in its event gathers. Data for all channels of the HRSN are now telemetered continuously from Parkfield to the BSL over the USGS T1 from Parkfield to Menlo Park, and over the NCEMC T1 from Menlo Park to Warren Hall.

The BSL uses the programs *qmaserv, seedlink,* and *scream* to collect data from data loggers. These programs receive data from remote Quanterra, Basalt and Guralp data loggers and redistribute it to one or more client programs. The clients include: *datalog*, which writes the data to disk files for archival purposes; *wdafill*, which writes the data to the shared memory region for processing with the network services routines that provide parameters to AQMS, the earthquake monitoring software system; and to other programs such as the DAC480 system feeding our helicorder and the feed for the Memento Mori Web page.

The two computers performing data acquisition are also "network services" computers that reduce waveforms for processing with the AQMS software (Figure 4.5.2). To facilitate processing, each system maintains a shared memory region containing the current 30 minutes of data for each channel.

Currently, BDSN data loggers from sites which use frame relay telemetry are configured to enable data transmission over a single frame relay T1 circuit to UCB, a possible point of failure. We formerly had a second T1 circuit, which was discontinued due to the decrease in funding from the State. For Quanterra data loggers, the *qmaserv* client program *cs2m* receives data and multicasts it over a private ethernet. The program *mcast* receives the multicast data from *cs2m*, and provides a *comserv*-like interface to local *comserv* clients. Thus, each network services computer has a *qmaserv* server for all stations, and each of the two systems has a complete copy of all waveform data.

The multicasting approach now handles data received from other types of data loggers and from other networks like the NCSN and UNR (University of Nevada, Reno). Data from partner networks are received by Earthworm data exchange programs, are converted to MiniSEED and are also multicast. On both network services computers, *mserv* receives multicast data and handles it just as it does BSL MiniSEED data.

In 2006, the BSL established a real-time data feed of all BSL waveforms between the BSL acquisition systems and the NCEDC computers using the open source Freeorb software. This allows the NCEDC to provide near-real-time access to all BSL waveform data through the NCEDC DART (Data Availabile in Real Time) system.

We monitor seismic stations and telemetry using the program *seisnetwatch*. This program extracts and displays current information such as time quality, mass positions, and battery voltage. If the parameter departs from the nominal range, the station is marked with yellow or red to indicate a possible problem.

Seismic Noise Analysis

BSL seismic data are routinely monitored for state of health. An automated analysis is computed regularly to characterize the seismic noise level recorded by each broadband seismometer. In addition, this year we took advantage of the April 1, 2014, M_w8.2earthquake off the northern coast of Chile to check noise levels at our STS-1 stations in the frequency band from 0.2 mHz to 2 mHz, by looking at the normal mode spectra (see Operational Section 4.1).

In 2000–2001, the BSL began to routinely monitor the Power Spectral Density (PSD) of ground motion recorded at its seismic stations (see past Annual Reports, http://earthquakes.berkeley.edu/annual_report/). The PSD provides an objective measure of background seismic noise characteristics over a wide range of frequencies. Observing it throughout the year also provides an objective measure of seasonal variation in noise characteristics and supports early diagnoses of instrumental problems.

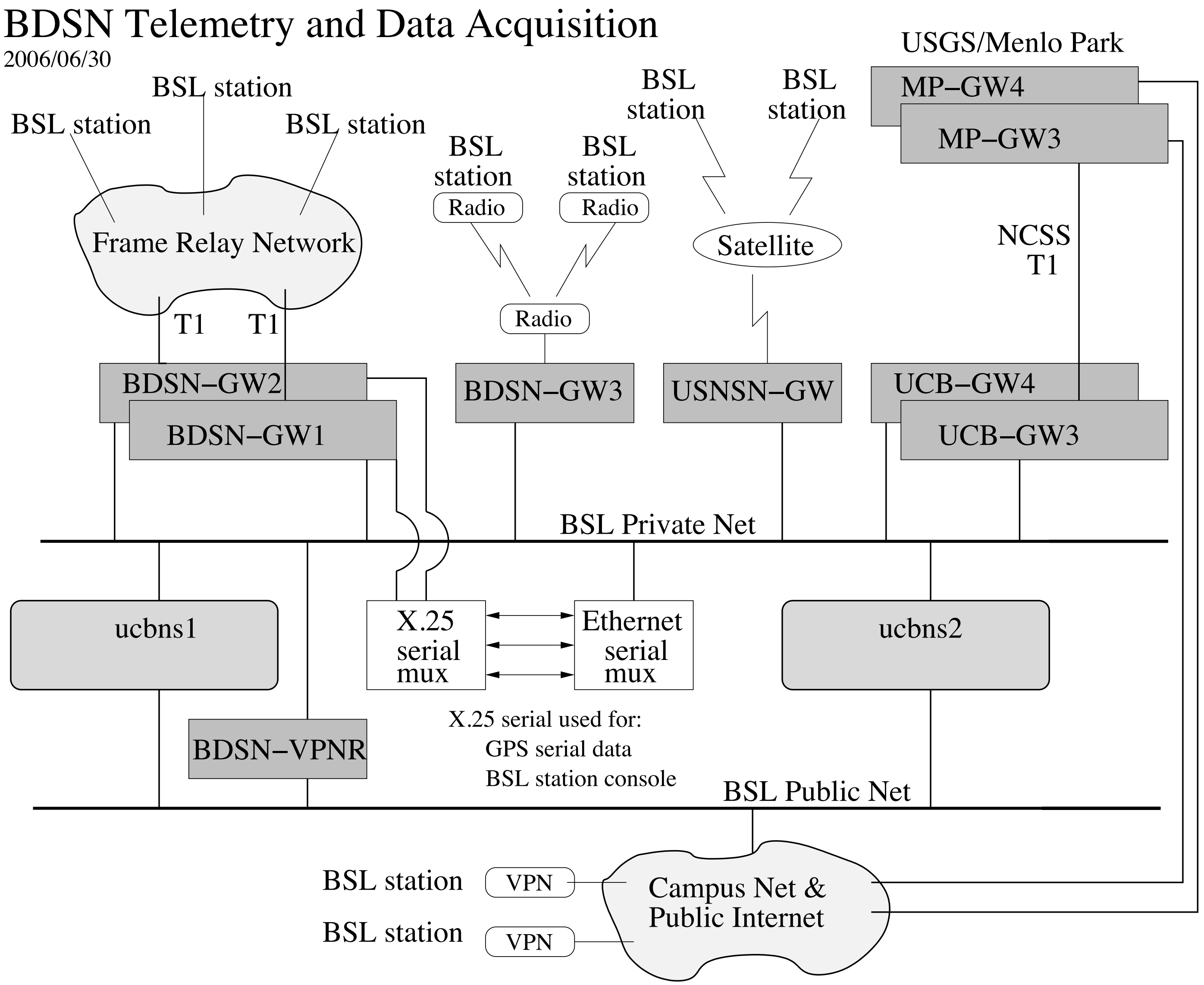

Figure 4.5.1: Data flow from the BDSN, NHFN, mPBO, HRSN, nad BARD networks into the BSL central processing facility.

The PSD estimation algorithm was developed at the BSL by Bob Uhrhammer in the early 1990s for characterizing the background seismic noise, and as a tool for quality control. That algorithm generates a bar graph output in which all the BDSN broadband stations can be compared by component. Cumulative PSD plots were generated for each station which showed the noise level in five frequency bands for the broadband channels. In addition to the station based plots, a summary plot was produced for each channel. Although we have moved to new noise monitoring procedures, these figures remain available on the web at http://earthquakes.berkeley.edu/seismo/bdsn/psd/, as they provide a record of equipment performance for the years 2000–2005.

Our main tool for monitoring seismic noise is now the Ambient Noise Probability Density Function (PDF) analysis system developed by *McNamara and Buland* (2004). This system performs its noise analysis over all the data of a given time period (week or year). The data processed include earthquakes, calibration pulses, and cultural noise. This is in contrast to Bob Uhrhammer's PSD analysis which looked at only the quietest portion of data within a day or week. Pete Lombard of the BSL extended the McNamara code to cover a larger frequency range and to support the many different types of sensors employed by the BSL. Besides the originally supported broadband sensors, our PDF analysis now includes surface and borehole geophones and accelerometers, strainmeters, and electric and magnetic field sensors. The enhancements to the PDF code, plus a number of bug fixes, were provided back to the McNamara team for incorporation in their work. The results of the PDF analysis are presented on our webpage at http://www.ncedc.org/ncedc/PDF/. The entry page now provides summary figures of the noise at each station for the BDSN and for other networks and stations we archive at the NCEDC. To provide an overview, figures are available for all components in two spectral bands, 32-128 s and 0.125-0.25 s for broadband sensors, and in the short period band for other sensors. This web page also provides access to the PDF plots for all stations, by network and component. In addition, each station's web page now provides

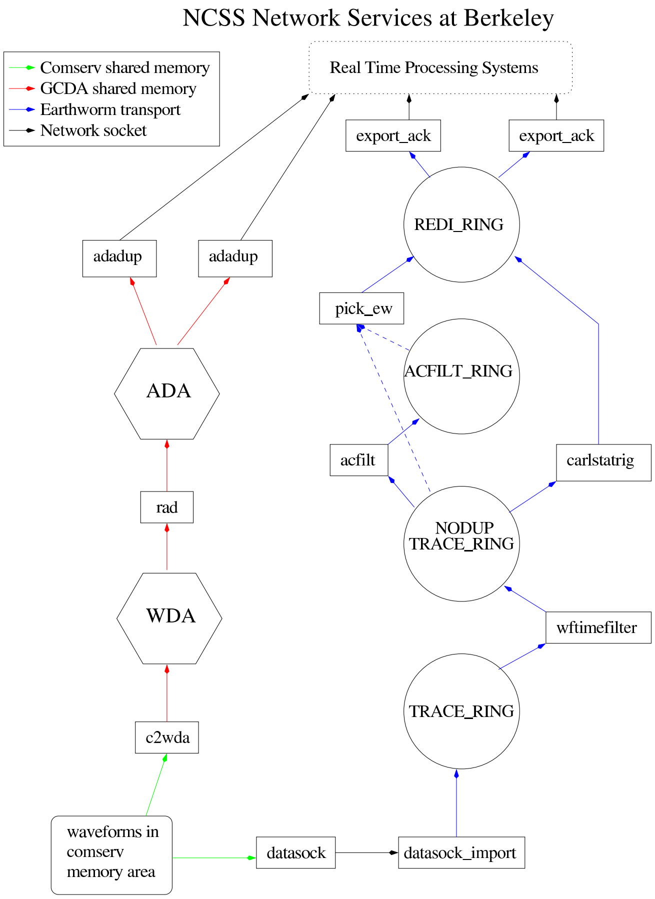

Figure 4.5.2: Flow of data from *qmaserv* areas through network services processing. One stream of the network services provides picks and an additional service provides associated codas determined using the programs shown in the right flow path. Every five seconds, ground motion parameters are also determined, including PGA, PGV, PGD, and ML100 (left flow column). Parameters from the network services are available to the AQMS software for event detection and characterization. Data are also logged to disk (via *datalog*), distributed to other computers (*mserv*), and spooled into a trace ring for export.

a summary of the noise performance of each channel (for an example, see the Data Quality tab at http://seismo.berkeley.edu/station_book/ybh.html).

Sensor Testing and Calibration

The BSL has an Instrumentation Test Facility in the Byerly Seismographic Vault where the characteristics of sensors can be systematically determined and compared. The test equipment consists of one or more six-channel Quanterra Q330 high-resolution data loggers and a custom interconnect panel. The panel 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. The vault also has a GPS rebroadcaster, so that all data loggers in the Byerly vault operate on the same time base. Upon acquisition of data at up to 200 sps from the instruments under test, PSD analysis, coherence analysis, and other analysis algorithms are used to characterize and compare the sensor performance. 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 assess the linearity of a seismic sensor. The BSL's sensor testing facility is described in detail in the 2001–2002 Annual Report (http://earthquakes.berkeley.edu/annual_report).

Testing STS-1 and STS-2 Sensors

In the past year, we have been testing several STS-1 sensors with hopes of replacing the slowly changing E-sensor at YBH. Three STS-1 seismometers (1 vertical, 2 horizontals) were set up in the Byerly Vault, along with an E300 electronics box and a STS-2 seismometer for testing purposes. Unfortunately, at the time of publication we have not yet been able to complete the testing as the individual sensors have not yet been responding properly.

TremorScope Geophone Cluster Test

Four three-component geophone packages with gimballed sensors will be installed in the TremorScope boreholes (see Research Section 2.34). During the spring, the geophone packages were temporarily connected to their respective cables. During two sessions the cables were connected by pigtails to the TremorScope data loggers and data were recorded on the Guralp EAM/DM24-6 units that will be used in the TremorScope deployments. During the first session, the geophones were strapped to a support in the Byerly Vault and recorded at 200 sps with a gain of 1 programmed in the data loggers (Figure 4.5.3). Because of problems with the data loggers and a dearth of interesting input signals, a second round of measurements were taken, with the geophone packages "emplaced" in sand and using a digitizer gain of 32. In neither case were the geophone packages placed so that the horizontal components had coherent orientations.

However, all sensors responded to ground movement. Initial results from both tests indicate that it will be important to know the exact response of each sensor for calculating the overall instrument response information, and for the correct rotation to compare sensor performance.

Monitoring Temporal Stability of Instrument Response in the BDSN

Monitoring the temporal stability of instrument response remains and important task at the BSL. We continue to evaluate sensor response as a function of time using the tools we have developed in the past years (see previous Annual Reports). For example, recent "sensor orientation" problems at KCC were discovered using these tools (see Operations Section 4.1).

We continue to monitor the response of the STS-1 seismometers operating in the BDSN. In the past year, fewer calibrations have been performed at the STS-1/E300 sites, since we have encountered challenges in communicating with the E300s following transitions away from frame relay telemetry.

Figure 4.5.3: The first geophone test in Byerly Vault, January 2014. The geophone borehole packages were strapped to the support between two instrument bays during the test.

A calibration of the sensors at KCC after telemetry was reinstated brought to light inconsistencies in our understanding of the orientation of the horizontal sensors. Following some remote sleuthing, we have corrected the instrument orientations in the database to reflect our understanding of the current status. On an upcoming site visit, we will investigate further and correct any inconsistencies in the hardware. It appears that there have been changes in the response of the E component at KCC, which we will also track down. We did perform a manual, on-site calibration at MHC, where we have original STS-1 factory electronics boxes. There the instrument response of the three sensors appears to be steady.

Acknowledgements

Doug Neuhauser, Bob Uhrhammer, Taka'aki Taira, Peggy Hellweg, Pete Lombard, Jennifer Taggart and Clay Miller are involved in the data acquisition and quality control of BDSN/HRSN/NHFN/mBPO data.

Bob Uhrhammer, Taka'aki Taira, Peggy Hellweg, Pete Lombard and Doug Neuhauser contributed to the preparation of this section.

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6 Bay Area Regional Deformation Network (BARD)

Introduction

The Bay Area Regional Deformation (BARD) network is a collection of permanent, continuously operating GPS receivers that monitor crustal deformation in the San Francisco Bay Area (SFBA) and Northern California. Started in 1991 with two stations spanning the Hayward Fault, BARD has been a collaborative effort of the Berkeley Seismological Laboratory (BSL), the USGS at Menlo Park (USGS/MP), and several other academic, commercial, and governmental institutions. The BARD network is designed to study the distribution of deformation in Northern California across the Pacific-North America plate boundary and interseismic strain accumulation along the San Andreas fault system in the Bay Area for seismic hazard assessment, and to monitor hazardous faults and volcanoes for emergency response management. It also provides data in real time for use in earthquake early warning (EEW) and rapid response applications. The BSL maintains and/or has direct continuous telemetry from 33 stations comprising the BARD Backbone, while additional stations operated by the USGS, US Coast Guard and others fill out the extended BARD network.

Since the completion of some major construction on the Plate Boundary Observatory (PBO) portion of EarthScope in 2004, the number of GPS stations in Northern California has expanded to over 250 (Figure 4.6.1). Together, PBO and BARD stations provide valuable information on the spatial complexity of deformation in the SFBA and Northern California, while the BARD network has the infrastructure and flexibility to additionally provide information on its temporal complexity over a wide range of time scales and in real time. All BARD Backbone stations collect data at 1 Hz sampling frequency and stream their data in real time to the BSL, where it is also provided to the public in real time. Furthermore, 18 BARD Backbone sites are collocated with broadband seismic stations of the BDSN, where they share continuous telemetry to UC Berkeley. As geodetic

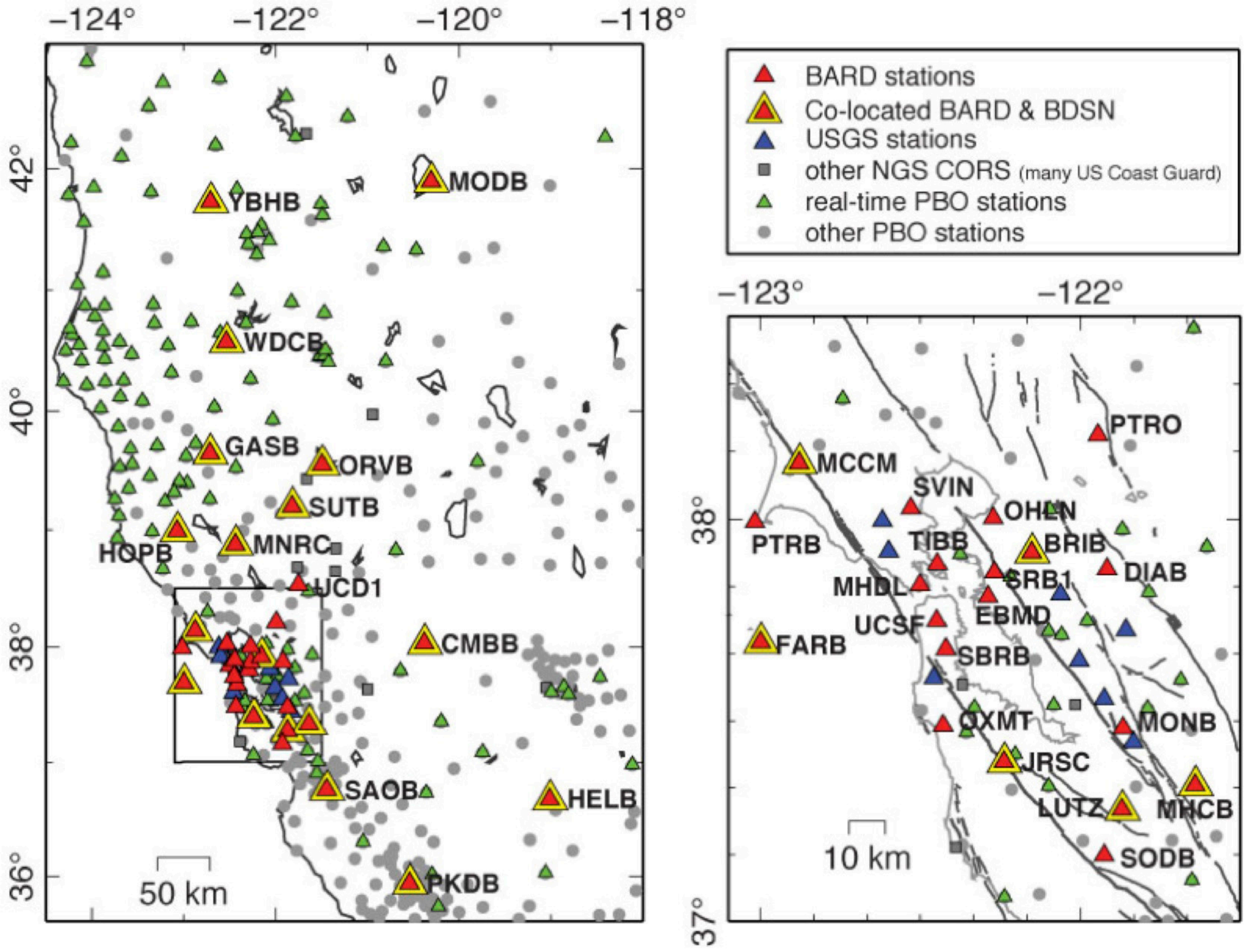

Figure 4.6.1: Map of the BARD Backbone network and surrounding PBO sites in Northern California. The box in the left figure indicates the extent of the figure on right.

and seismic data become more closely integrated, these collocated stations are already available to provide combined data products.

Station configuration

The BARD network includes two models of receiver: Trimble NetRS and Topcon Net-G3A. All BARD stations use a radome equipped, low multipath choke-ring antenna, designed to provide security and protection from weather and other natural phenomena, and to minimize differential radio propagation delays. A low-loss antenna cable is used 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.

All BARD stations are continuously telemetered to the BSL. Many use frame relay technology, either alone or in combination with radio telemetry. However, with frame relay being phased out by telecommunication companies, we have been seeking alternatives. This year, stations BRIB and CMBB were moved off of frame relay to internet based methods. BRIB is now received over a T1 line shared through an agreement with UC Berkeley's Department of Astronomy. Station CMBB, which is on the grounds of Columbia College, is now connected through the college's campus internet. Both of these have been reliable for regular daily use.

Other telemetry methods in the BARD network include direct radio link to Berkeley and satellite telemetry. At MODB, MCCM, and MNRC we are able to telemeter 1 Hz data using the USGS VSAT system that collects seismic broadband data as part of the National Seismic Network (NSN).

BARD station monumentations broadly fall into three types. Most are anchored into bedrock, either directly or via a steel-reinforced concrete cylinder. The five "mini-PBO" stations that are still operated by the BSL are collocated with USGS strainmeters and the GPS antennas are bolted onto the borehole casing using an experimental mount developed at the BSL, which has since been adopted by PBO for their strainmeter sites. Four sites (UCD1, SRB1, UCSF, SBRB) are located on the roofs of buildings. Most of the last type have been installed in the past four years, and their stability over long periods of time is yet to be evaluated. Six stations installed under the American Recovery and Reinvestment Act (ARRA) have PBO style short-brace monuments cemented into bedrock.

New Station—HELB

In December 2013 we finished installation of a new station, HELB, located in the Sierra Foothills (Figure 4.6.1), which had been postponed several times due to weather. It is a short-brace monument, cemented into hard rock and has a clean sky view (Figure 4.3). The overall RMS for daily processing has been low (6.9-7.3 mm), however there is not yet enough data to fully analyze the position stability. HELB is situated on a private residence, and data is telemetered by radio from the field site to the house and then is sent on to the BSL over satellite connection. Data collection, archival and streaming have all been fully implemented for HELB; daily RINEX files are available from the NCEDC and real-time streams are available through our NTRIP caster.

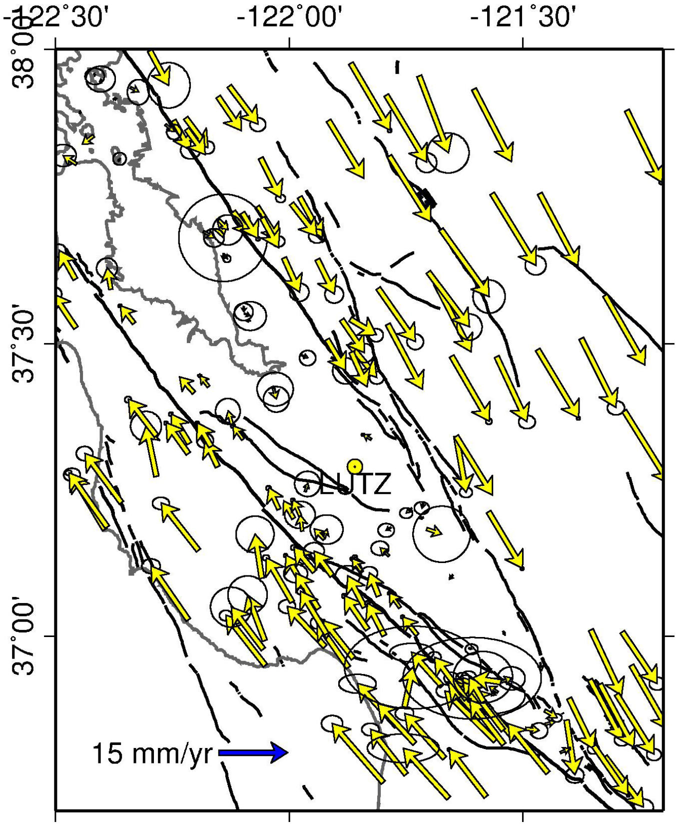

Figure 4.6.2: Velocities from BAVU3β, including BARD stations, as well as campaign, and PBO stations. Yearly velocities are relative to station LUTZ, marked by a yellow circle.

Data Handling

Archival

Raw and RINEX data files from the 33 BARD Backbone stations and several other stations run by BARD collaborators, such as the USGS and LBNL, are archived at the Northern California Earthquake Data Center (NCEDC). The data are checked to verify their integrity, quality, completeness, and conformance to the RINEX standard, and are then made accessible, usually within 1 hour of the end of the UTC day, to all participants and other members of the GPS community through the internet, both by anonymous FTP and through the internet (http://ncedc.org/). BARD data are also available to the community through the GPS Seamless Archive Centers (GSAC), such as that hosted by the Scripps Orbit and Permanent Array Center (SOPAC, http://gsac.ucsd.edu). High-rate raw data are also decimated to create 15 s RINEX data files. 1 Hz RINEX files are available for all BARD Backbone sites after May 2010.

As part of the activities funded by the USGS through the BARD network, the NCEDC has established an archive of the 10,000+ survey mode occupations collected by the USGS since 1992 and the NCEDC is the principal archive for this dataset. These and other survey mode data are used together with data from BARD and PBO stations to produce BAVU (Bay Area

Site	Lat. (deg)	Lon. (deg)	Receiver	Telem.	Samp. Rate	Colloc. Net.	Location
BRIB	37.92	-122.15	NETRS	T1	1 Hz	BDSN	Briones Reservation, Contra Costa County
CMBB	38.03	-120.39	NET-G3A	Int	1 Hz	BDSN	Columbia College, Tuolumne County
DIAB	37.88	-121.92	NETRS	FR	1 Hz		Mt. Diablo , Contra Costa County
EBMD	37.82	-122.28	LEICA	R	1 Hz		East Bay MUD Headquarters, Alameda County
FARB	37.70	-123.00	NETRS	R-FR	1 Hz	BDSN	Farallon Island , San Francisco County
GASB	39.65	-122.72	NET-G3A	R-FR	1 Hz	BDSN	Alder Springs, Glenn County
HELB	36.68	-119.02	NET-G3A	R/VSAT	1 Hz	BDSN	Miramonte
HOPB	39.00	-123.07	NET-G3A	R/FR	1 Hz	BDSN	Hopland Field Station, Mendocino County
JRSC	37.41	-122.23	NET-G3A	Int	1 Hz	BDSN	Jasper Ridge Biological Preserve, San Mateo County
LUTZ	37.29	-121.87	NET-G3A	FR	1 Hz	BDSN	SCC Communications , Santa Clara County
MCCM	38.14	-122.88	NET-G3A	VSAT	1 Hz	BDSN	Marconi Conference Center, Marin County
MHCB	37.34	-121.64	NETRS	FR	1 Hz	BDSN	Lick Observatory, Santa Clara County
MHDL	37.84	-122.49	NETRS	R/FR	1 Hz	mini-PBO	Marin Headlands, Marin County
MNRC	38.88	-122.44	NET-G3A	VSAT	1 Hz	BDSN	McLaughlin Mine, Lake County
MODB	41.90	-120.30	NETRS	VSAT	1 Hz	BDSN	Modoc Plateau , Modoc County
MONB	37.50	-121.87	NET-G3A	FR	1 Hz		Monument Peak, Santa Clara County
OHLN	38.01	-122.27	NET-G3A	FR	1 Hz	mini-PBO	Ohlone Park, Contra Costa County
ORVB	39.55	-121.50	NET-G3A	FR	1 Hz	BDSN	Oroville , Butte County
OXMT	37.50	-122.42	NET-G3A	FR	1 Hz	Mini-PBO	Ox Mountain , San Mateo County
PKDB	35.95	-120.54	NETRS	R/T1	1 Hz	BDSN	Bear Valley Ranch, Monterey County
PTRB	38.00	-123.01	NETRS	R/FR	1 Hz		Point Reyes Lighthouse , Marin County
PTRO	38.21	-121.94	NET-G3A	FR	1 Hz		Potrero Hills, Solano County
SAOB	36.77	-121.45	NETRS	FR	1 Hz	BDSN	San Andreas Observatory, San Benito County
SBRB	37.69	-122.41	NET-G3A	FR	1 Hz	mini-PBO	San Bruno Replacement, San Mateo County
SODB	37.17	-121.93	NET-G3A	R/FR	1 Hz		Soda Springs, Santa Clara County
SRB1	37.87	-122.27	NET-G3A	Fiber	1 Hz		Seismic Replacement Building, Alameda County
SUTB	39.21	-121.82	NETRS	R/FR	1 Hz	BDSN	Sutter Buttes , Sutter County
SVIN	38.03	-122.53	NET-G3A	R/FR	1 Hz	mini-PBO	St Vincents , Marin County
TIBB	37.89	-122.45	NET-G3A	R/Int	1 Hz		Tiburon , Marin County
UCD1	38.54	-121.75	NETRS	Int	1 Hz		UC Davis , Yolo County (operated by UC Davis)
UCSF	37.76	-122.46	NET-G3A	FR	1 Hz		UC San Francisco , San Francisco County
WDCB	40.58	-122.54	NET-G3A	FR	1 Hz	BDSN	Whiskeytown Dam, Shasta County
YBHB	41.73	-122.71	NETRS	FR	1 Hz	BDSN	Yreka Blue Horn Mine, Siskiyou County

Table 4.6.1: List of BARD stations maintained by the BSL. The receivers operating now are: Trimble NETRS, (NETRS) and Topcon Net-G3A (Net-G3A). Site EBMD, operated by the East Bay Municipal Utility District, has a Leica GX1230 receiver and Leica AR10 antenna. The telemetry types listed are FR = Frame Relay, R = Radio, Int = Internet, VSAT = Satellite, T1 = Private T1 line. Telemetry often includes a radio hop from the GPS site to the seismic vault, indicated by an initial R. All (except EBMD) are equipped with Ashtech or Topcon choke ring antennas.

Velocity Unification), a united set of continuous and survey data from the wider San Francisco Bay Area, processed under identical conditions using GAMIT (*d'Alessio et al., 2005).*

Data from five of our sites (HOPB, MHCB, CMBB, OHLN, and YBHB) are sent to the National Geodetic Survey (NGS) in the framework of the CORS (Continuous Operating Reference Stations) project (http://www.ngs.noaa.gov/CORS/). The data from these five sites are also distributed to the public through the CORS FTP site.

Real-time Streaming

All BARD stations are available in real time with 1 Hz data sampling; a step toward our goal of integrating GPS with the Northern California Seismic System (NCSS) for use in hazard assessment and emergency response and for Earthquake Early Warning applications. Data streams are received from the stations in BINEX format and converted into RTCM using Sharc software package (maintained by USGS, Pasadena). Both the original BINEX and RTCM streams are then made available to the public from an Ntrip-caster operated by the BSL (http://seismo.berkeley.edu/bard/realtime). The BSL also acts as a conduit for real-time streams for seven continuous GPS stations operated by the USGS, Menlo Park and five stations installed by the Lawrence Berkeley National Lab (LBNL), in order to make those data easily accessible to the GPS community.

Interseismic Velocities and Daily Time Series

Average station coordinates are estimated from 24 hours of observations for BARD stations and other nearby continuous GPS sites using the GAMIT/GLOBK software developed at MIT and SIO (*Herring et al.*, 2010a & b). GAMIT uses double-difference phase observations to determine baseline distances and orientations between ground-based GPS receivers. Ambiguities are fixed using the widelane combination followed by the narrowlane, with the final position based on the ionospheric free linear combination (LC). Baseline solutions are loosely constrained until they are combined togeth-

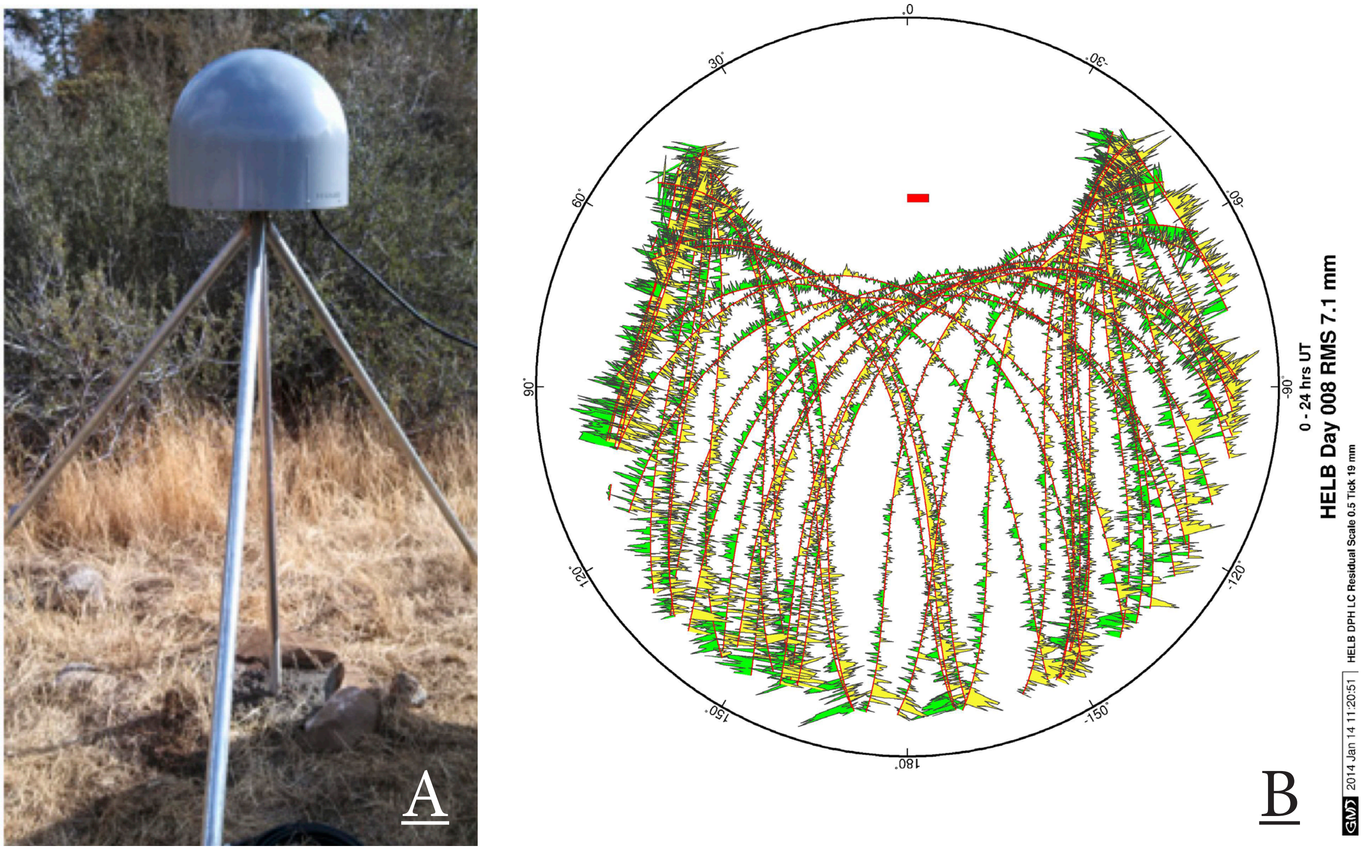

Figure 4.6.3: A) Photo of station HELB showing completed monumentation. B) Phase residual plot from daily processing for HELB on 1/8/2014. This shows the goodness of fit for observations throughout the day. Small excursions from the red lines (orbit tracks) indicate phase measurements that are well fit by a stable position. The plot is oriented such that the north direction is at the top.

er. GAMIT produces solutions as "H-files", which include the covariance parameters describing the geometry of the network for a given day and summarize information about the sites. We combine daily, ambiguity-fixed, loosely constrained H-files using the Kalman filter approach implemented by GLOBK (*Herring*, 2010b). They are combined with solutions from the IGS global network and PBO and stabilized in an ITRF2005 reference frame. The estimated relative baseline determinations typically have 2-4 mm long term scatter in the horizontal components and 10-20 mm scatter in the vertical.

BARD data are an important component of the Bay Area Velocity Unification (BAVU) project (*d'Alessio et al.*, 2005). BAVU contains all available campaign data in Northern California and processes them in a consistent manner to produce a comprehensive and high-density velocity map. It relies on a network of CGPS stations to provide a framework on which these data can be combined. With data going back to 1992, BARD stations can provide such a framework (Figure 4.6.2). Average linear velocities for each station are estimated from monthly combinations of the campaign, BARD, PBO and IGS solutions and are shown in Figure 4.6.2.

Time series of station positions are produced with daily, automated updates. BARD data are processed within 24 hours using IGS rapid orbit information and the time series are updated immediately. When rapid PBO and IGS global station solutions become available (usually within 2-3 days), they are combined with the rapid BARD solutions using GLOBK and the time series is again updated. Final processing with both GAMIT and GLOBK occurs when IGS final orbits and final PBO solutions become available (1-2 weeks); the time series is then updated for the last time with the final positions.

After each update, the time series are cleaned by removing outliers and common mode noise. Common mode noise is estimated by stacking the difference between observations and modeled motion for all stations. The model is derived from *a priori* values for station velocity, coseismic offsets and postseismic decay. The cleaned data is then used to re-estimate the *a priori* model parameters in an iterative process. Outliers are identified as points whose misfit to a linear trend is greater than 4 s on any single component of motion (North, East, or Up). Overall time series scatter is low; with average RMS values across the BARD network of 1.8 mm, 2.9 mm, and 5.8 mm for the north, east and up directions respectively. Plots of station time series are posted daily on the BARD website (http://seismo.berkeley.edu/bard/timeseries).

Earthquake Early Warning and Rapid Response

With support from the Gordon and Betty Moore Foundation, we have been working on integrating information from GPS into earthquake early warning (EEW) algorithms in a module we call G-larms. Our goals for this project include establishing a robust system for processing GPS data streams

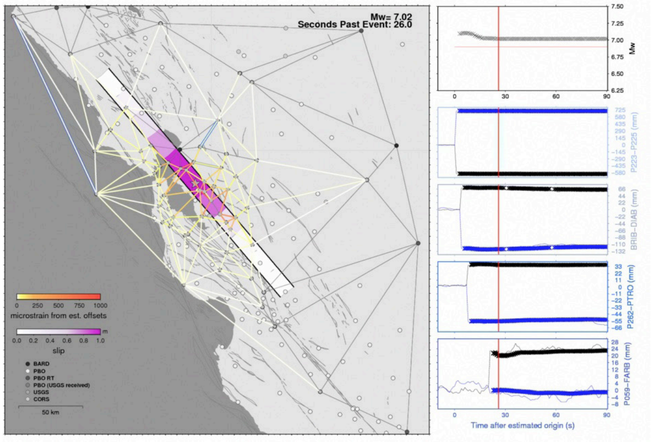

Figure 4.6.4: Snapshot during a real-time test of G-larms; the red line on the right side shows the timing of the snapshot. Top right figure shows the estimated earthquake magnitude for the slip model in magenta on the left. The test is based on a simulated *M*6.9 earthquake. G-larms begin estimating position after the S-wave arrival (blue and black symbols). Offsets are updated and input into an inversion for fault slip every second. Testing was run in true real time; synthetic offsets were added to GPS position time series on-the-fly in order to capture true real time noise and data availability.

into displacement time series and designing and implementing methods to use these results to supplement seismic earthquake early warning systems during large earthquakes.

The BSL is currently using data from 62 GPS stations in the greater San Francisco Bay Area to generate real time position estimates on a routine basis. This includes 26 stations that are operated as part of the BARD network and 8 that are operated by the USGS, Menlo Park. We also process 29 stations operated by the Plate Boundary Observatory (PBO), who collect real time data for a subset of their stations and make these publicly available over the internet.

We use trackRT, together with predicted orbits from the International GPS service (IGS) to produce high sample rate displacement time series with 2-4 second latency. TrackRT was developed at MIT and is based on GAMIT/GLOBK, which we use for daily processing (*Herring et al.*, 2010a). TrackRT follows a network processing approach, with displacements generated with respect to a reference station. The benefits of this approach are that common noise sources, such as local atmosphere, are canceled out, leading to more precise relative displacements.

We employ a fully triangulated network scheme in which neighboring station pairs are processed individually, such that no station serves as the universal reference site (Figure 4.6.4). This makes our network resilient against an outage or telemetry loss at any individual station. The low processing overhead of trackRT makes it possible for us to run separate instances of the program to produce displacement time series for all ~160 baselines in our network. The scatter in the displacement time series for each baseline depends on distance and increases during days with changeable weather conditions. However, it is often within 2 cm over the course of 24 hours, which is considered a stable result.

This past year we reached a major milestone in our progress toward integrating GPS information into earthquake early warning, with our GPS module, G-larms, which now provides the final link between GPS stations in the field and a deliverable earthquake warning. G-larms actively monitors the incoming GPS position estimates and calculates mean position and variance in a five-minute rolling buffer. When it receives an earthquake alert from the seismic system it records the current mean position as the pre-event value and then begins to measure the post-event position as it evolves. Static offsets "arrive" at a location concurrently with the S-wave, therefore G-larms waits until the estimated S-wave arrival time to begin calculations (see right side of Figure 4.6.4).

Once the offsets are estimated, they are input into a model inversion for slip on a fault. The fault location is determined from the epicenter estimated by the seismic alert system and its orientation is determined based on the tectonic regime of the epicenter. Assuming these values allows the underlying calculations to remain linear and helps the inversion to run quickly (within one second). As shown in Figure 4.6.4, in a test that occurred in true real time and included true real time data noise, G-larms determined the magnitude of a synthetic earthquake within 0.1 magnitude units within 20 seconds following the event origin. Similar tests using real data from the 2010 *M*7.2 El Mayor-Cucapah earthquake show that even in the presence of shaking (and with the difficult station distribution at the US-Mexico border) the earthquake magnitude can be well estimated within 40 seconds.

While real time processing of GPS data is capable of providing measurements of displacement within seconds of its occurrence, post-processing provides results with lower noise levels, leading to better precision. This leads to better estimates of the finite fault plane, which when used with ShakeMap provides more accurate shaking estimates than a point source model. Rapid post-processing (RPP) techniques can be used to estimate static offsets from moderate to large earthquakes, which will constrain a non-linear search for fault plane parameters. Rapid post-processing requires waiting 1-2 minutes after the earthquake for data to accumulate, but displacement time series can then be generated within 5 minutes using the software Track, developed at MIT. From these, full fault plane determination can be performed within another 5 minutes. While real-time processing techniques are critical for using GPS data for Earthquake Early Warning, rapid post-processing provides higher precision in the static offset measurement. This allows GPS data to be used for smaller earthquakes and still finishes within a time frame appropriate for ShakeMap.

GPS-Seismograms for Large Earthquakes

An M_w6.9 earthquake offshore of Northern California on March 10, 2014 provided an opportunity to investigate the ability of GPS stations in Northern California to resolve dynamic shaking from a large event. Although most stations

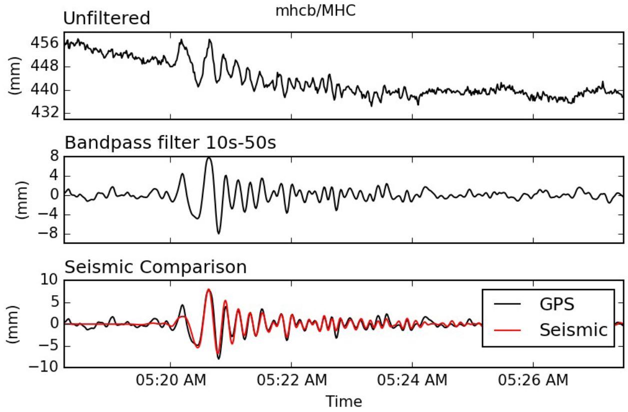

Figure 4.6.5: Comparison of BARD network high-rate GPS timeseries and data from a broadband seismometer at site MHCB in the Marin Headlands. The transverse component of motion is shown (motion perpendicular to azmuthal direction to the earthquake's epicenter).

were too far away to resolve a measurable static offset, dynamic motions with amplitudes of 1-2 cm were felt within the network. 1 Hz data is routinely collected and archived for BARD and USGS stations, however high-rate data is only downloaded from PBO stations for special events. In response to the earthquake, UNAVCO triggered a download for all stations in California and archived these data in their public FTP site.

I. Johanson, in Research Section 2.32, shows the results of this analysis in more detail. Nonetheless, where GPS and seismic equipment are collocated, the two match very well, providing confidence in the accuracy at non-collocated sites (Figure 4.6.5). The results represent a marked increase in spatial density of long-period motions (2 Hz and lower), which otherwise are measured only by broadband seismometers. As shown in the report by Johanson, the dense data set reveals detail in the subsurface structure that is otherwise missed by the sparsely distributed broadband seismic instruments.

Acknowledgements

Ingrid Johanson and Richard Allen oversee the BARD program. Joshua Miller, Sarah Snyder, John Friday, Doug Neuhauser, Mario Aranha, Jennifer Taggart and Clay Miller contributed to the operation of the BARD network in 2013–14. Operation of the BARD network is partially supported by funding from the USGS/NEHRP program grant #G10AC00141. Real-time data processing is supported by a grant from the Moore Foundation.

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7 Northern California Earthquake Monitoring

Introduction

Earthquake information production and routine analysis in Northern California have been improving over the past two decades. Since June 2009, the BSL and the USGS in Menlo Park have been operating mirrored software systems (see 2010 Annual Report). For this system, processing begins as the waveforms arrive at the computers operating the real time, or AQMS, software, and ranges from automatic preparation of earthquake information for response to analyst review of earthquakes for catalogs and quality control.

This is the most recent step in a development at the BSL that began in the mid-1990s with the automated earthquake notification system called Rapid Earthquake Data Integration (REDI, *Gee et al.*, 1996; 2003a). That system determined earthquake parameters rapidly, producing near real time locations and magnitudes for earthquakes in Northern and Central California, estimated rupture characteristics and the distribution of ground shaking following significant earthquakes, and provided tools for the rapid assessment of damage and estimation of loss.

A short time later, in 1996, the BSL and the USGS began collaborating to produce information for Northern and Central California earthquakes. Software operating in Menlo Park and Berkeley were merged to form a single, improved earthquake notification system using data from both the NCSN and the BDSN (see past annual reports). Since 2000, the USGS and the BSL operate as the Northern California Earthquake Management Center (NCEMC) of the California Integrated Seismic Network (Operational Section 4.2).

With support from the USGS and the Gordon and Betty Moore Foundation, the BSL is now also participating in the development and assessment of a statewide prototype Earthquake Early Warning system. A fully fledged system will provide warning of imminent ground shaking in the seconds after an earthquake has initiated but before strong motion begins at sites that may be damaged. This Annual Report has several Research Studies describing the project (???put in references here.)

Northern California Earthquake Management Center

In this section, we describe how the Northern California Earthquake Management Center fits within the CISN system. Figure 4.2.3 in Operational Section 5.2 illustrates the NCEMC as part of the CISN communications ring. The NCEMC is a distributed center, with elements in Berkeley and in Menlo Park. The 35 mile separation between these two centers is in sharp contrast to the Southern California Earthquake Management Center, where the USGS Pasadena is located across the street from the Caltech Seismological Laboratory.

As described in Operational Section 5.2, the CISN partners are now connected by an internet based communications link. The BSL has maintained two T1 communication links with the USGS Menlo Park as robust and reliable links for shipping waveform data and other information between the two processing systems.

Figure 5.7.1 provides more detail on the system operating at the NCEMC since mid-June, 2009. Currently, complete earthquake information processing systems operate in parallel in Menlo Park and Berkeley. Incoming data from each network are processed locally at each of the two data centers in network services computers. The continuously reduced data, which include picks, codas, ground motion amplitudes, and ML100, are exchanged between the data centers and fed into both processing streams. Real time analysis is coordinated using up-to-date information from the local real time database, which is replicated to the local data center database. Event review and automatic downstream processes, such as computation of fault plane solutions, access the internal data center databases. To maintain redundancy, robustness, and completeness, these two databases replicate with each other across the San Francisco Bay. They also replicate with the public database from which information is made available to the public. The system includes the production of location and origin time as well as estimates of M_d, M_L, and M_w. For events with $M \geq 3.5$, ShakeMaps are also calculated on two systems, one in Menlo Park and one in Berkeley. Finite fault calculation is not yet integrated into the new processing system. It is only calculated at the BSL at this time.

This system combines the advantages of the NCSN with those of the BDSN. The dense network of the NCSN contributes to rapid and accurate earthquake locations, low magnitude detection thresholds, and first-motion mechanisms. The high dynamic range data loggers, digital telemetry, and broadband and strong-motion sensors of the BDSN provide reliable magnitude determination, moment tensor estimation, calculation of peak ground motions, and estimation of source rupture characteristics. Robust preliminary hypocenters, or "Quick Looks" are published within a few tens of seconds of the origin time. Event information is updated when preliminary coda magnitudes are available, within 2-4 minutes of the origin time. Estimates of local magnitude are generally available a few seconds later, and other parameters, such as the peak ground acceleration and moment magnitude, follow within 1-4 minutes (Figure 5.7.2).

During the past year, we made the transition from distributing earthquake information through the Earthquake Information Distribution System (EIDS) to using the Product Distribution Layer (PDL). The earthquake information is available on the web and, as a push service through the Earthquake Notification Service (http://sslearthquake.usgs.gov/ens). Now all information products for ongoing earthquake activity are transferred to the USGS in Golden, CO. We are working on the tools and standards for the transfer of historical earthquake information, event and associated products from past earthquakes to complete the "Comprehensive Catalog" (ComCat) that will be hosted by the USGS. We are also developing readers and writers for QuakeML. For organizations which need very rapid access to earthquake information, the CISN Display is a useful tool

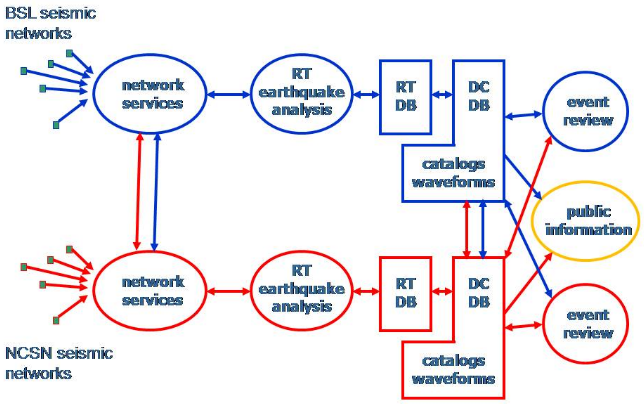

Figure 5.7.1: Details of the Northern California earthquake information processing system. Network services processing, that is, production of picks, ground motion amplitudes, and other reduced information, occurs at both datacenters, and the information is exchanged. Complete earthquake information processing systems exist on both sides of the San Francisco Bay, and up-to-date information is exchanged by database replication.

(http://www.cisn.org/software/cisndisplay.htm). The USGS has upgraded its earthquake information site with a new url as has the BSL (http://earthquakes.berkeley.edu). The public will have an easier time navigating to the word "earthquakes" than the old "seismo". These web sites provide valuable resources for information which are useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

Earthquake Information Processing

In June 2009, we began operating the ANSS Quake Monitoring System (AQMS) software, formerly CISN Software, as the production system in the Northern California Seismic System (NCSS) for monitoring and reporting on Northern California earthquakes. This came as the result of a long effort to adapt and test software developed for the TriNet system operating in Southern California.

Data flow in the Northern California system (Figure 5.7.3) allows for our diverse forms of data acquisition as well as variability in network distribution. In addition, the BSL and the USGS have minimized the use of proprietary software in the system.

One exception is the database program, Oracle. The NCEDC Oracle database hosts all earthquake information and parameters associated with the real time monitoring system. It is the centerpoint of the system, providing up-to-date information to all processing modules. Reliability and robustness are achieved by continuously replicating the databases. The public, read-only, database provides event and parametric information to catalog users and to the public.

During the last few years, BSL staff members, particularly Pete Lombard, have become extremely familiar with elements of the TriNet software. The software is now adapted for Northern California, with many adjustments and modifications completed along the way. For example, Pete Lombard adapted the TriNet magnitude module to Northern California. Pete has made a number of suggestions on how to improve the performance of various modules of AQMS and has worked closely with Caltech and the USGS in Pasadena on modifications.

The BSL and the USGS Menlo Park are exchanging "reduced amplitude time series". One of the important innovations of the TriNet software development is the concept of continuous processing (*Kanamori et al.*, 1999). Waveform data are constantly processed to produce Wood Anderson synthetic amplitudes and peak ground motions. A program called *rad* produces a reduced time series, sampled every 5 seconds, and stores it in a memory area called an "Amplitude Data Area" or ADA. Other modules can access the ADA to retrieve amplitudes to calculate magnitude and ShakeMaps as needed. The BSL and the USGS Menlo Park have collaborated to establish tools for ADA-based exchange. The first step toward improving reliability and robustness, by implementing ADA exchange with Southern California, was taken in June 2014, with a draft proposal on implementation.

2013–2014 Activities

Moment Tensor Solutions with *tmts* and Finite Fault Analysis

The BSL continues to produce moment tensor solutions and to perform finite fault analysis for quakes with M_w>6.0. We use the package, *tmts,* which is a Java and web based moment tensor processing system and review interface based on the complete waveform modeling technique of *Dreger and Romanowicz* (1994). The web based review interface has been operating in Northern California since July 2007, and the automatically running version for real time analysis since June 2009. The version of *tmts* currently operating in Northern California allows full inversions that include an isotropic element of the source, i.e. explosions or collapses. From July 2013 through June 2014, BSL analysts reviewed many earthquakes in Northern California and adjoining areas of magnitude 2.9 and higher. Reviewed moment tensor solutions were obtained for 70 of these events (through 6/30/2014). Figure 5.7.4 and Table 5.7.2 display the locations of earthquakes in the BSL moment tensor catalog and their mechanisms. During this year, no finite fault inversions were produced for Northern California earthquakes.

We are currently developing a new version of the moment tensor system which will permit the use of records from strong motion sensors.

StationXML development

Just as the exchange of earthquake information is now based on the transfer of QuakeML, a XML schema describing earthquake-related parameters, information and metadata describing a station can be more completely encompassed using a XML schema called StationXML. The schema being used is based on one developed by the Federation of Digital Seismograph Networks (FDSN), however, we have extended it to encompass pa-

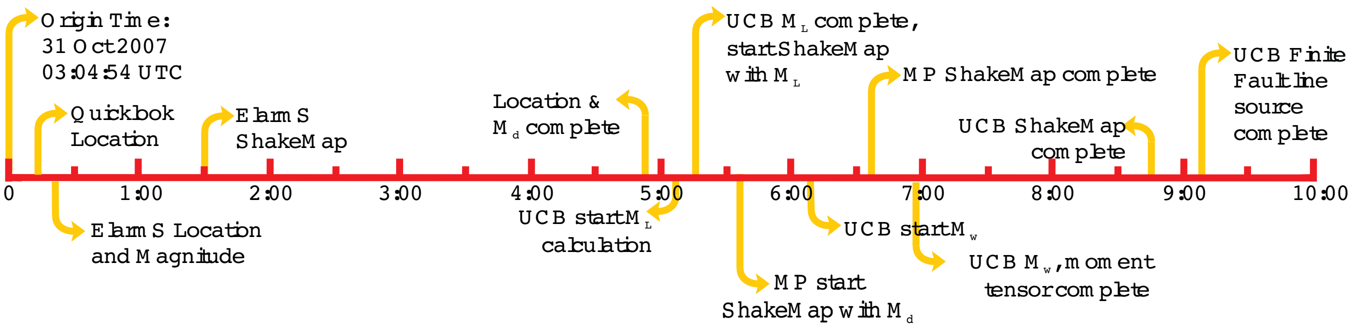

Figure 5.7.2: Illustration of the earthquake products timeline for the M_w 5.4 Alum Rock earthquake of October 30, 2007. Note that all processing was complete within 10 minutes of the origin time.

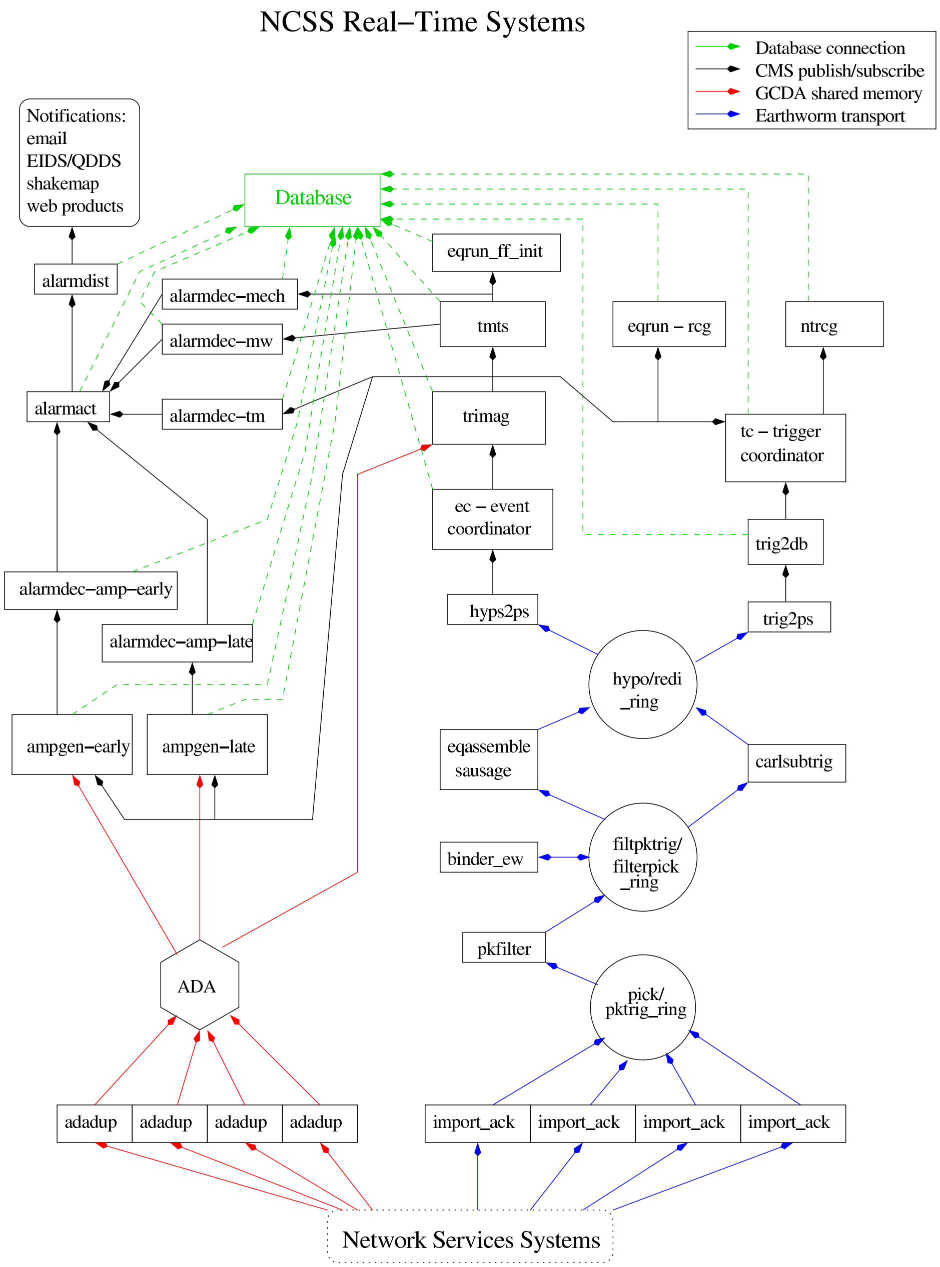

Figure 5.7.3: Schematic diagram of processing in the NCSS system. The design combines elements of the Earthworm, TriNet, and REDI systems.

rameters needed to describe parameters used in engineering seismology as well. The BSL has written both readers for importing parameters from StationXML into the AQMS database system, as well as writers for taking station information from the AQMS system and putting it into StationXML and its extensions. Progress on the development and use of the Station Information System (SIS) proposed by Southern California would not be as rapid without these contributions from the BSL.

Implementation of GridMT

GridMT, a grid-search based system for searching for earthquakes, particularly large earthquakes, offshore of Northern California and Oregon, has now been operating in "production mode" for several years. We regularly review the events it produces and compare the GridMT locations and moment tensor solutions with those from the AQMS system. We hope to implement GridMT into the production system soon.

EEW in the Production System

In production mode the Earthquake Early Warning System (EEW) will be running in parallel and in conjunction with the AQMS earthquake information system. In Northern California, we have been slowly moving elements of the EEW system into the production AQMS environment. In particular, in the past year we have moved the EEW waveform processing onto production machines in Menlo Park and at UCB, to improve reliability and robustness. We are very pleased to note that improvements to the ElarmS processing, and the use of one second packets from the Q330 data loggers has allowed us to produce earthquake alerts for several earthquakes in the Los Angeles area within five seconds of the earthquakes' onset (see Research Sections 3.30 and 3.29).

M_L project

Local magnitude, or M_L, remains an important parameter to describe earthquake size and continuity between new and old earthquake catalogs. In Northern California, we have only been using data from the horizontal components of broadband and strong motion sensors, since the implementation of the new CISN magnitude system. For the past several years, we have been making progress toward the calibration of local magnitude parameters for both the horizontals of geophones and short-period sensors, where they are available, and for the use of vertical sensors. When these parameters are available, we expect to be able to provide M_L values for many of the small earthquakes in The Geysers, for example, that are currently too small for duration magnitudes (M_d).

Moving AQMS to the Linux Environment

AQMS was developed under the Solaris environment. This environment has become more challenging during the past few years for a variety of reasons. In the previous year, Pete Lombard reviewed all the AQMS software in use in Northern California in the Linux environment, and produced a package that compiled and ran for more than a year. This year, we made the decision to begin to transition our production system to Linux. Just at the end of the year, the first production computers were configured and brought into service. We expect to complete the process for UCB and Menlo Park real time production computers during the next few months.

Routine Earthquake Analysis

In fiscal year 2013-2014, almost 35,000 earthquakes were detected and located by the automatic systems in Northern California. This compares with more than 32,000 in 2012–2013, 27,000 in 2011–2012 and over 25,000 in 2010–2011. Of these events, 172 had preliminary magnitudes of three or greater. 29 events had M_L or M_w greater than four. The largest event, on March 10, 2014, offshore of Ferndale, had a magnitude of 6.8. Many of the events with magnitude greater than 4 were aftershocks of this earthquake (see Table 5.7.1 for more details). 47 ShakeMaps were also produced for earthquakes in our region of responsibility during this fiscal year.

Although BSL staff no longer read BDSN records for local and regional earthquakes (see Annual Report of 2003-2004), they now participate in timing and reviewing earthquakes with *Jiggle*, mainly working on events from past sequences that have not yet been timed. This work contributes to improving the earthquake catalog for Northern California, but also ensures robust response capabilities, should the Menlo Park campus be disabled for some reason.

Acknowledgements

Peggy Hellweg oversees our earthquake monitoring system and directs the routine analysis. Peter Lombard and Doug Neuhauser contribute to the development of software, and Stephane Zuzlewski manages the databases. Peggy Hellweg, Taka'aki Taira, Ingrid Johanson, Doug Dreger, Sierra Boyd, Cheng Cheng, Andrea Chiang, Brent Delbridge, Scott French, Mong-Han Huang, Chris Johnson, Qingkai Kong, Clay Miller, Avinash Nayak, Jennifer Strauss, Jennifer Taggart, and Zhou (Allen) Zheng contribute to the routine analysis of moment tensors. Peggy Hellweg and Doug Neuhauser contributed to the writing of this section. Partial support for the development, implementation and maintenance of the AQMS software, as well as for the production of earthquake information, is provided by the USGS under Cooperative Agreement G10AC00093, and from the California Office of Emergency Services.

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Gee, L., D. Neuhauser, D. Dreger, M. Pasyanos, B. Romanowicz, and R. Uhrhammer, The Rapid Earthquake Data Integration System, *Bull. Seis. Soc. Am., 86*, 936-945, 1996.

Pasyanos, M., D. Dreger, and B. Romanowicz, Toward real-time estimation of regional moment tensors, *Bull. Seis. Soc. Am., 86*, 1255-1269, 1996.

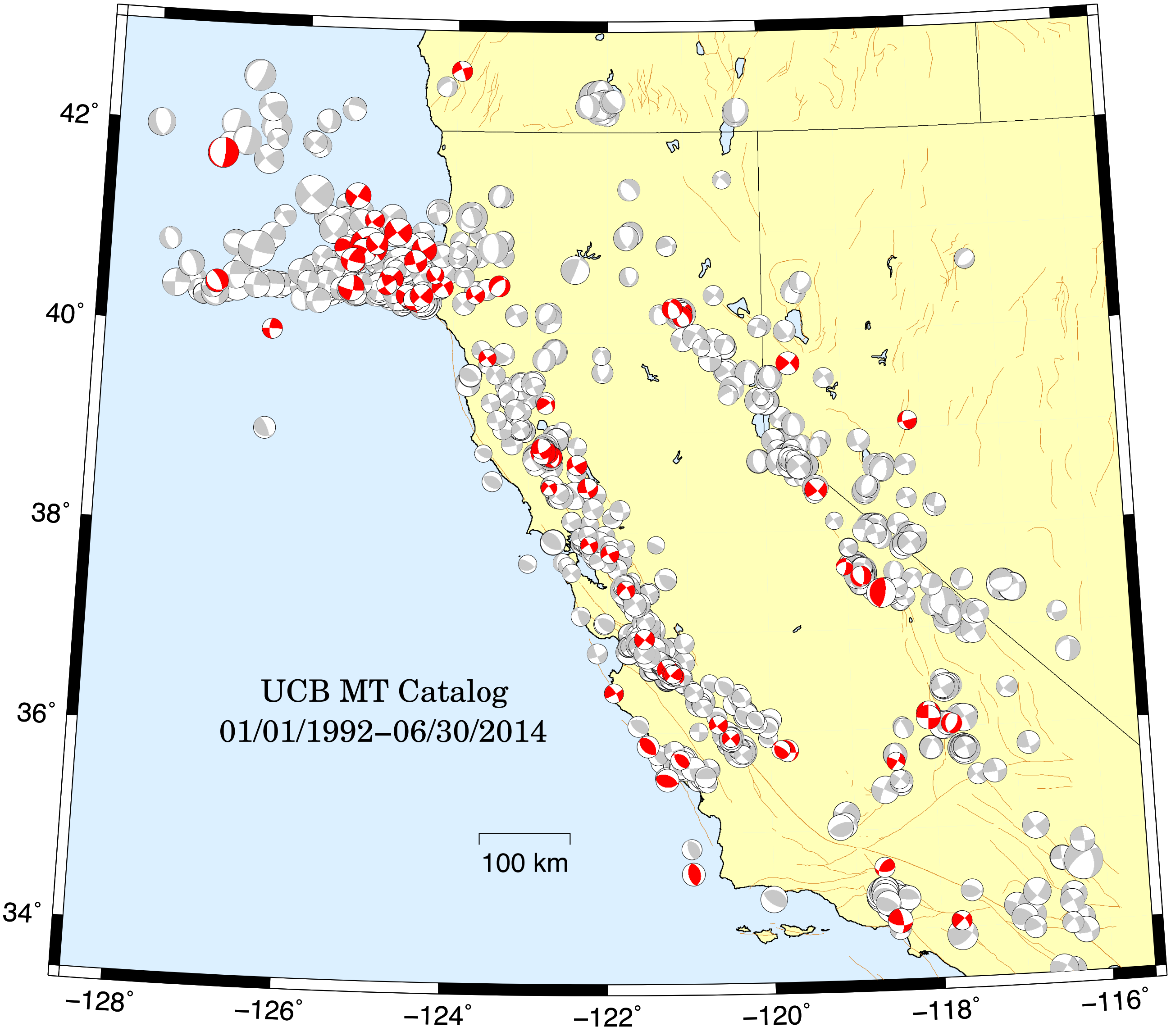

Figure 4.7.4: Map comparing reviewed moment tensor solutions determined by the BSL from past years (gray) with those from the fiscal year 2012-2013 (red/dark).

Location	Date	UTC Time	Lat.	Lon.	MT Depth	M_L	M_w	M_o	Str.	Dip	Rake
Ridgemark, CA CA	7/3/2013	09:05:00 PM	36.64	-121.26	14	3.35	3.7	4.44E+21	234	89	7
Greenville, CA	7/7/2013	6:31:32 AM	40.21	-121.02	3.5	3.13	3.35	1.30E+21	305	78	-167
The Geysers, CA	7/14/2013	010:40:38 PM	38.81	-122.79	3.5	3.35	3.7	4.35E+21	256	86	17
East Foothills, CA	7/15/2013	07:02:44 PM	37.43	-121.77	8	3.36	3.28	1.04E+21	328	72	-161
The Geysers, CA	7/18/2013	1:16:10 AM	38.81	-122.82	3.5	3.1	3.5	2.19E+21	40	56	-56
Westhaven-Moonstone, CA	7/18/2013	10:02:30 AM	41.09	-125.06	18	3.09	3.5	2.20E+21	229	85	30
Soledad, CA	7/19/2013	4:07:02 AM	36.57	-121.16	5	3.02	3.19	7.52E+20	233	78	27
Santa Rosa, CA	7/24/2013	12:13:00 AM	38.45	-122.74	8	0	2.87	2.49E+20	323	79	-161
The Geysers, CA	7/25/2013	010:36:38 PM	38.81	-122.81	1.5	2.85	3.25	9.44E+20	176	51	-119
Bayview, CA	8/3/2013	2:25:50 AM	40.81	-124.4	18	3.92	4.47	6.39E+22	56	89	-20
Coalinga, CA	8/6/2013	03:02:33 PM	36.08	-120.64	5	3.3	3.35	1.33E+21	54	90	-16
Greenville, CA	8/19/2013	11:08:19 AM	40.15	-121.03	1.5	3.27	3.43	1.76E+21	295	67	-125
Greenville, CA	8/19/2013	11:09:55 AM	40.16	-121.03	3.5	3.5	3.63	3.43E+21	316	57	-120
Vandenberg AFB	8/24/2013	1:16:31 AM	34.59	-120.96	5	4.21	4.1	1.75E+22	167	51	88
Spanish Springs, NV	8/27/2013	12:51:44 AM	39.68	-119.68	11	4.43	4.23	2.73E+22	47	81	12
The Geysers, CA	8/28/2013	4:43:05 AM	38.76	-122.71	1.5	3.59	3.76	5.42E+21	162	58	-91
West Bishop, CA	9/6/2013	09:08:54 PM	37.36	-118.58	8	3.26	3.34	1.55E+24	10	68	93
Ferndale, CA	9/9/2013	010:37:18 PM	40.81	-125.43	18	3.64	4.02	1.34E+22	66	75	51
Hayfork, CA	9/24/2013	09:36:34 PM	40.46	-123.41	36	3.46	3.84	7.23E+21	232	55	-66
Cobb, CA	10/2/2013	08:38:32 PM	38.83	-122.8	1.5	3.11	3.12	5.98E+20	40	62	-62
Rio Dell, CA	10/4/2013	02:42:07 PM	40.44	-124.15	27	3.71	3.9	8.75E+21	231	81	-13
Berkeley, CA	10/7/2013	4:26:08 AM	37.88	-122.23	8	2.97	2.99	3.82E+20	327	89	175
Wofford Heights, CA	10/10/2013	1:34:23 AM	35.67	-118.48	8	3.52	3.34	1.29E+21	299	79	168
Bayview, CA	10/11/2013	011:05:37 PM	40.98	-124.75	24	4.91	4.94	3.24E+23	231	89	7
Berkeley, CA	10/15/2013	8:07:27 AM	37.88	-122.23	5	3.05	3.15	6.66E+20	331	85	-171
Soledad, CA	10/19/2013	4:02:24 AM	36.6	-121.21	11	3.27	3.38	1.46E+21	133	89	178
Mammoth Lakes, CA	10/21/2013	05:04:11 PM	37.53	-118.83	8	4.23	3.75	5.25E+21	2	62	-66
Laytonville, CA	10/26/2013	1:29:26 AM	39.74	-123.55	8	0	3.23	8.61E+20	145	87	175
Crescent City, CA	11/8/2013	10:46:56 AM	41.33	-125.29	3.5	4.45	4.65	1.17E+23	211	89	7
San Ramon, CA	11/13/2013	05:30:31 PM	37.79	-121.97	11	3.29	3.32	1.20E+21	244	81	14
The Geysers, CA	11/14/2013	8:47:18 AM	38.79	-122.76	1.5	3.19	3.43	1.72E+21	317	70	-153
Ferndale, CA	11/17/2013	010:45:010 PM	40.31	-124.56	14	3.29	3.65	3.71E+21	19	88	24
Redway, CA	11/21/2013	12:48:55 AM	40.37	-123.72	33	3.1	3.41	1.62E+21	55	86	-20
Gilroy, CA	12/2/2013	10:05:22 AM	36.94	-121.54	8	3.91	3.65	3.66E+21	129	88	-175
Angwin, CA	12/6/2013	6:44:55 AM	38.68	-122.39	8	3.67	3.65	3.71E+21	242	88	26
Lost Hills, CA	12/13/2013	7:49:57 AM	35.81	-119.8	21	4.16	4.08	1.65E+22	97	78	64
Ferndale, CA	12/17/2013	01:28:02 PM	40.69	-124.51	21	3.94	4.11	1.85E+22	161	85	-166
Ferndale, CA	12/24/2013	10:28:50 AM	40.51	-124.82	11	3.82	4.3	3.54E+22	220	85	9
Ferndale, CA	1/2/2014	6:23:010 AM	40.29	-124.45	24	3.64	4.02	1.32E+22	100	87	172
The Geysers, CA	1/2/2014	9:32:28 AM	38.79	-122.74	1.5	3.08	3.25	9.40E+20	209	54	-65
The Geysers, CA	1/12/2014	08:24:47 PM	38.81	-122.82	3.5	4.01	4.53	7.76E+22	345	57	-136
The Geysers, CA	1/21/2014	11:11:12 AM	38.84	-122.84	1.5	3.54	3.74	5.15E+21	65	65	-29
Ferndale, CA	1/23/2014	4:10:41 AM	40.41	-125.34	8	4.24	4.63	1.09E+23	8	78	-13
Mammoth Lakes, CA	2/5/2014	9:08:06 AM	37.63	-119.03	8	3.01	3.06	4.82E+20	10	74	-132
Ferndale, CA	2/6/2014	2:55:42 AM	40.29	-124.51	18	3.16	3.56	2.73E+21	90	55	-100

Cambria, CA	2/6/2014	07:42:21 PM	35.53	-121.27	5	4.27	4.13	1.98E+22	293	52	100
Coalinga, CA	2/14/2014	03:07:23 PM	35.94	-120.49	11	3.15	3.2	7.86E+20	321	89	-175
Cambria, CA	2/27/2014	06:52:30 PM	35.87	-121.5	8	4.32	4.06	1.55E+22	131	45	82
Carmel-by-the-Sea, CA	3/8/2014	12:53:20 PM	36.4	-121.92	3.5	3.72	3.43	1.75E+21	60	82	16
Ferndale, CA	3/10/2014	5:18:13 AM	40.83	-125.13	18	5.82	6.8	2.00E+26	318	88	-169
Ferndale, CA	3/10/2014	9:42:43 AM	40.76	-125.21	8	3.31	3.64	3.59E+21	105	75	148
Ferndale, CA	3/10/2014	9:54:26 AM	40.83	-125.12	3.5	3.34	3.71	4.53E+21	47	78	-99
Ferndale, CA	3/10/2014	10:28:19 AM	40.78	-125.19	14	4.22	4.47	6.21E+22	33	76	22
Ferndale, CA	3/10/2014	10:46:23 AM	40.66	-125.3	5	3.49	3.46	1.96E+21	62	77	22
Ferndale, CA	3/10/2014	03:16:29 PM	40.45	-124.88	18	3.24	3.65	3.70E+21	57	85	160
Kernville, CA	3/13/2014	2:11:05 AM	36.1	-118.06	5	4.62	4.41	5.04E+22	182	90	-172
Ferndale, CA	3/14/2014	04:32:35 PM	40.35	-124.61	21	3.58	4	1.24E+22	33	86	5
Bayview, CA	3/16/2014	3:46:010 AM	40.86	-125.02	5	3.72	4.01	1.30E+22	133	77	-155
Westwood, CA	3/17/2014	01:25:35 PM	34.08	-118.5	8	4.63	4.42	5.40E+22	353	69	147
Ferndale, CA	3/18/2014	10:33:59 AM	40.69	-125.33	21	3.96	4.41	5.09E+22	105	78	151
Ferndale, CA	3/19/2014	9:57:08 AM	40.31	-124.51	5	3.53	3.95	1.04E+22	166	76	47
Soledad, CA	4/1/2014	6:41:35 AM	36.59	-121.19	8	3	3.27	9.98E+20	225	82	26
Upper Lake, CA	4/2/2014	04:27:05 PM	39.28	-122.79	5	2.88	3.34	1.26E+21	53	83	45
Yountville, CA	4/4/2014	4:04:55 AM	38.45	-122.25	8	3.56	3.63	3.50E+21	163	77	-151
Chester, CA	5/12/2014	1:14:44 AM	40.24	-121.16	8	3.57	3.67	3.95E+21	187	56	-53
Smith Valley, NV	5/30/2014	7:48:33 AM	38.41	-119.36	11	4.3	4.02	1.34E+22	319	90	164
Ferndale, CA	6/2/2014	011:54:20 PM	40.35	-124.42	18	3.87	4.14	2.04E+22	224	88	15
Cambria, CA	6/3/2014	8:53:43 AM	35.73	-121.11	5	3.48	3.5	2.18E+21	144	56	108
Ferndale, CA	6/25/2014	05:00:26 PM	40.56	-124.25	24	0	3.2	7.86E+20	140	73	-141
Kettleman City, CA	6/25/2014	010:01:36 PM	35.82	-119.88	11	3.21	3.37	1.43E+21	301	68	69

Table 5.7.1: Moment tensor solutions for significant events from July 1, 2012 through June 30, 2013 using a complete waveform fitting inversion. Epicentral information is from the UC Berkeley/USGS Norhtern California Earthquake Management Center. Moment is in dyne-com and depth is in km.

8 Northern California Earthquake Data Center

Introduction

The Northern California Earthquake Data Center (NCEDC) is a permanent archive and distribution center primarily for multiple 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 NCEDC was formed as a joint project of the Berkeley Seismological Laboratory (BSL) and the U.S. Geological Survey (USGS) at Menlo Park in 1991, and current USGS funding is provided under a cooperative agreement for seismic network operations.

Time series data come from broadband, short period, and strong motion seismic sensors, and geophysical sensors such as electromagnetic sensors, strain meters, creep meters, atmospheric pressure, pore pressure, water level, and wind speed sensors. Earthquake catalogs can include event time, hypocenters, magnitudes, moment tensors, mechanisms, phase arrivals, codas, and amplitude data. GPS data are available in both raw observables and RINEX formatted data.

The NCEDC also provides support for earthquake processing and archiving activities of the Northern California Seismic System (NCSS), which includes the seismic networks of UC Berkeley, USGS Menlo Park, and other partners contributing seismic data from northern and central California. The NCSS earthquake processing system and the NCEDC are part of the Northern California Earthquake Management Center (NCEMC), which is one of three earthquake management centers in the California Integrated Seismic Network (CISN). The CISN is the California regional organization of the USGS Advanced National Seismic System (ANSS).

2013–2014 Activities

By its nature, data archiving is an ongoing activity. In 2013–2014, the NCEDC continued to expand its data holdings and enhance access to the data. Projects and activities of particular note:

- Continued to develop and install production Web services for the distribution of station metadata using Station XML, waveform inventory, and miniSEED data at http://service.ncedc.org. The latest webservice, ncedc-eventdata, delivers pre-assembled waveforms for events listed in the NCSS and EGS catalogs.
- Continued receiving, archiving, and distributing event information (hypocenter, magnitude, phase, and amplitude data) and waveforms for the DOE Enhanced Geothermal Systems (EGS) monitoring project.
- Continued to support the NCEMC earthquake analysis by providing real-time access to earthquake parameters and waveforms from the NCEDC for the CISN
- Continued work with the NCSN and USGS National Strong Motion Program (NSMP) to import the metadata and build dataless SEED volumes for all NSMP dialup and triggered stations.
- Developed an extended stations XML writer to facilitate exporting existing station metadata maintained by the NCEDC to the newly developed ANSS Station Information System (SIS).
- Finished the development of programs to convert EarthScope SAFOD vertical strain time series data to miniSEED format, processed three TBytes of SAFOD vertical strain data collected from May 2007 through December 2013, and delivered the resulting miniSEED data to the IRIS DMC.
- Database schema enhancements to accommodate double-difference origins and the addition of double-difference locations to the NCSS catalog.

Data Types and Contributors

Table 4.8.1 and Figure 4.8.1 provide a breakdown of the NCEDC data by data type.

BDSN/NHFN/mPBO Seismic Data

The BDSN (Operational Section 5.1), NHFN (Operational Section 5.3), and Mini-PBO (Operational Section 5.6) stations (all network code BK) send real-time data from 65 seismic data loggers to the BSL. These data are written to disk files, used by the CISN AQMS software for real-time earthquake processing and by the prototype CISN ShakeAlert earthquake early warning (EEW) system, and delivered to the DART (Data Available in Real Time) system at the NCEDC, where they are immediately available to anyone on the internet. Continuous high-rate data (200-500 samples/second) are now available for all of the NHFN borehole seismic data channels. All time series data from the Berkeley networks continue to be processed and archived by an NCEDC analyst using *calqc* quality control procedures in order to provide the highest quality and most complete data stream for the NCEDC archive. The recent upgrade to the BDSN stations increased the onsite storage at each site, which allows us to recover data from the station after telemetry outages and improve the completeness of the BDSN data archive.

NCSN Seismic Data

The USGS Northern California Seismic Network (NCSN) continuous waveform data from USGS Menlo Park are converted to MiniSEED, transferred in real time to the NCEDC via the internet, and made available to users immediately through the NCEDC DART and NCEDC web services. NCSN event waveform data, as well as data from all other real time BSL and collaborating networks, are automatically collected by the NCSS waveform archiver and stored at the NCEDC for event review

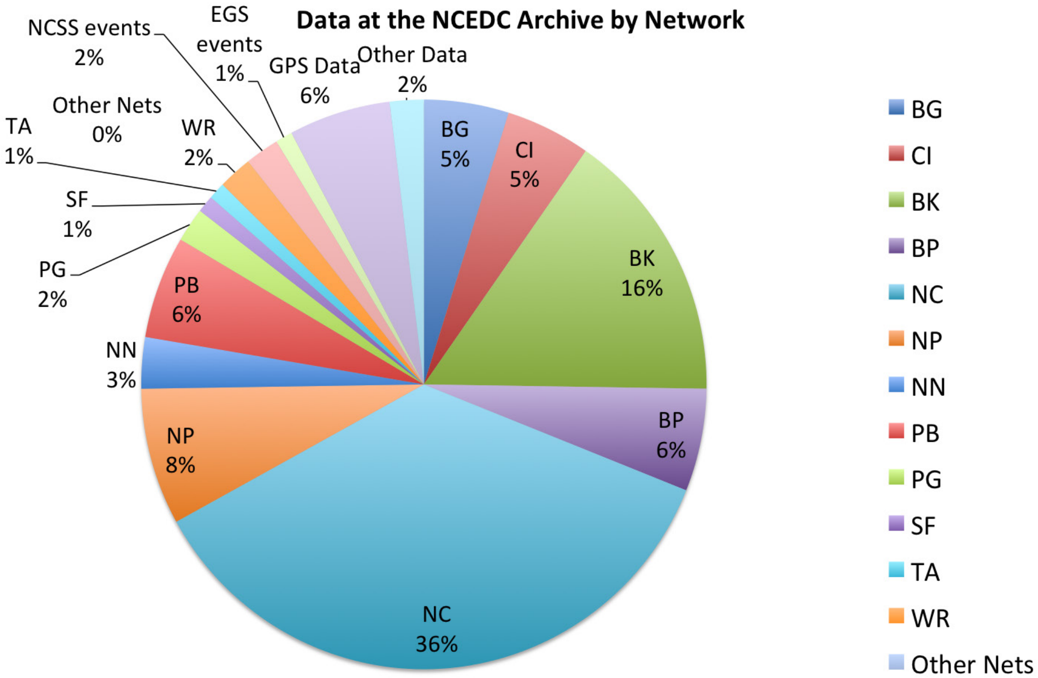

Figure 4.8.1: Chart showing the relative proportion of each data set at the NCEDC. BK - Berkeley Digital Seismic Network; BP - Berkeley High-resolution Seismic Network in Parkfield; NCSN - Northern California Seismic Network and collaborators; CI - Southern California Seismic Network; NN - University of Nevada, Reno Seismic Network; GPS - various GPS datasets, including BARD; EarthScope - data from various EarthScope activities; Other - various small data sets.

Data Set (Net or Collection)	Total Data Archive Size(GB)	Percent of Archive
BG	3,837.55	4.68%
BK	13,018.89	15.87%
BP	5,004.54	6.1%
CI	3,762.78	4.59%
NC	30,330.59	36.96%
NN	2,795.98	3.41%
NP	6,394.37	7.79%
PB	4,945.03	6.03%
PG	1,433.39	1.75%
SF	527.49	0.64%
TA	656.34	0.8%
WR	1,396.79	1.7%
Other Nets	105.79	0.13%
NCSS events	1,306.81	1.59%
EGS events	497.24	0.61%
GPS Data	4,559.71	5.56%
Other Data	1,484.23	1.81%
Total	82,057.53	100%

Table 4.8.1: Volume of data archived at the NCEDC by network code.

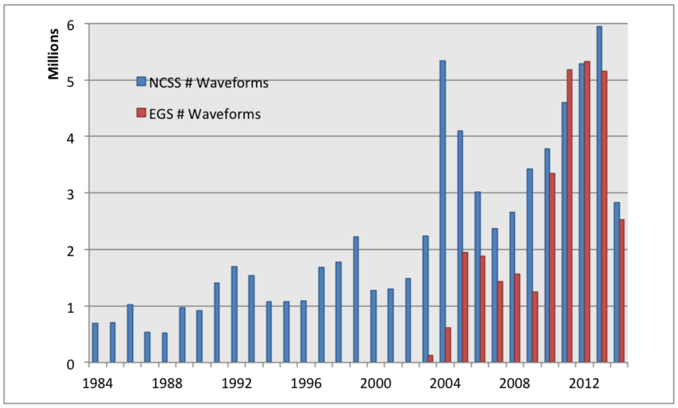

Figure 4.8.2: Number of events in the NCSS and EGS event catalogs by year.

and analysis and for distribution to users. All NCSS time series data are archived in miniSEED format.

Improvements in the acquisition of NCSN data, described in the 2005–2006 BSL Annual Report, enabled the NCEDC to start archiving continuous NCSN waveforms in early 2006. We then started the process of reading and archiving continuous NCSN waveforms from previous years that had been saved on tapes. We completed the continuous waveform archiving of NCSN tape data from 1993 through 2005 in 2013.

Parkfield High Resolution Seismic Network (HRSN) Data

The history of upgrades to the acquisition and archival of HRSN data can be found in the 2010–2011 BSL Annual Report. We continue to archive continuous 250 and 20 sample-per-second data from the HRSN stations. The most recent HRSN station upgrade added 16 GB of local storage at each site, which allows us to recover data from the station after telemetry outages, and greatly improves the completeness of the HRSN data archive.

EarthScope Plate Boundary Observatory (PBO) and SAFOD Time Series Data

The NCEDC was one of two funded archives for PBO EarthScope borehole and laser strain data. Strain data are collected from all of the PBO strain sites and are processed by UNAVCO. miniSEED data are delivered to the NCEDC using SEEDLink, whereas raw and XML processed data are delivered to the NCEDC using Unidata's Local Data Manager (LDM). The miniSEED data are inserted into the NCEDC DART and are subsequently archived from the DART. UNAVCO provides EarthScope funding to the NCEDC to help cover the processing, archiving, and distribution costs for these data. In early 2010, the NCEDC began receiving and archiving all of the continuous seismic waveform data from the PBO network to complement the PBO strain data. The seismic data are received from an Antelope ORB server at UNAVCO and converted from their native format to miniSEED on a data import computer. The data are then transferred via the SEEDLink protocol to the NCEDC, inserted into the NCEDC DART for immediate internet access, and subsequently archived from the DART.

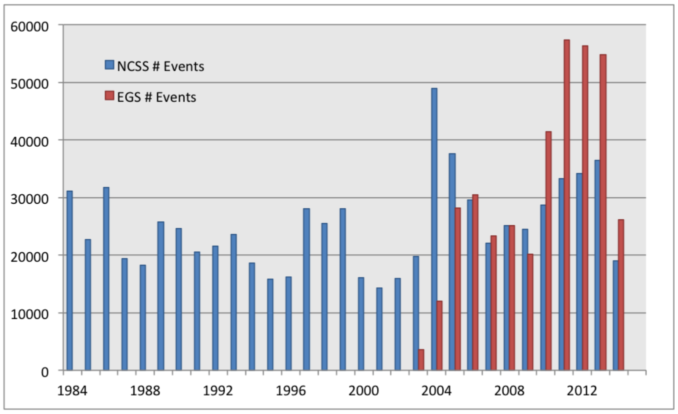

Figure 4.8.3: Number of waveforms for events in the NCSS and EGS event catalogs by year.

The NCEDC was an archive center for the SAFOD event data and has also processed the continuous SAFOD data. Starting with the initial data in July 2002 from the SAFOD Pilot Hole, and later, data from the SAFOD Main Hole, the NCEDC converted data from the original SEG-2 format data files to miniSEED, and developed the SEED instrument responses for this data set. Continuous four kHz data from SAFOD written to tape at SAFOD were periodically sent to the BSL to be converted, archived, and forwarded to the IRIS DMC (IRIS Data Management Center). SAFOD EarthScope funding to the NCEDC is to cover the processing, archiving, and distribution costs for these data. A small subset of the continuous SAFOD data channels are also incorporated into the NCSN, and are available in real time from the NCEDC DART, and are archived at the NCEDC, and are forwarded to the IRIS DMC. After the failure of the SAFOD permanent instrument in September 2008, the USGS deployed a temporary network in the Main Hole, and the NCEDC continued to process and archive these data. Both the permanent and temporary seismic instruments were removed in mid-2010 in order to analyze the failure of the permanent SAFOD instrument packet, but the temporary seismic instruments were reinstalled in late 2010 and continue to send data for distribution and archiving to the NCEDC.

Through a UNAVCO EarthScope contract, the NCEDC developed software to convert raw data from the SAFOD vertical laser strainmeter operated by UCSD to miniSEED format for long term archiving and distribution. By the end of 2013, the NCEDC finished the process of converting ~three TBytes of SAFOD vertical strain data collected from May 2007 through December 2013 to miniSEED format. The miniSEED data and metadata for all channels were delivered to the IRIS DMC for permanent archiving and distribution.

Due to a significant cut in UNAVCO's EarthScope funding, UNAVCO discontinued all funding for NCEDC EarthScope data processing and archiving activities at the end of 2013. As of January 2014, the NCEDC is only archiving PBO seismic data channels that are used by the NCSS earthquake processing system.

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 selected UNR stations. The data are transmitted in real time from UNR to UC Berkeley, where they are made available for CISN real time earthquake processing and for archiving. Initially, some of the stations were sampled at 20 Hz, but all stations are now sampled and archived continuously at 100 Hz.

The NCEDC installed Simple Wave Server (SWS) software at UNR, which provides an interface to UNR's recent collection of waveforms. The SWS is used by the NCEDC to retrieve waveforms from UNR that were missing at the NCEDC due to real time telemetry outages between UNR and UC Berkeley.

In early 2006, the NCEDC started to archive continuous data from the UNR short-period stations that are contributed to the NCSN. Both the broadband and short-period UNR stations contributed to the CISN are available in real time through the NCEDC DART.

Electro-Magnetic Data

The NCEDC continues to archive and process electric and magnetic field data acquired at several UC Berkeley sites. The BSL operates both magnetic and electric field sensors at SAO. However, most of these channels have been down for repair during the 2010–2011 year. In collaboration with Professor Simon Klemperer at Stanford, we acquire magnetic and electric field channels at BSL sites JRSC and BRIB, and magnetic field channels at site MHDL. The three magnetic field channels and either two or four electric field channels are digitized at 40 Hz, 1 Hz, and 0.1 Hz, and are telemetered in real-time along with seismic data to the Berkeley Seismological Laboratory, where they are processed and archived at the NCEDC in a similar fashion to the seismic data.

GPS Data

The NCEDC continues to archive GPS data through the BARD (Bay Area Regional Deformation) network of continuously monitored GPS receivers in Northern California (Operational Section 5.6). The NCEDC GPS daily archive now includes 80 continuous sites in Northern California. Of these, there are ~32 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 the East Bay Municipal Utilities District, the City of Modesto, the National Geodetic Survey, and the Jet Propulsion Laboratory (JPL).

In addition to the standard 15 second continuous GPS data files, the NCEDC is now archiving and distributing high-rate 1 Hz continuous GPS data from all of the BSL-operated BARD stations. In collaboration with UC San Diego Scripps Institution of Oceanography (UCSD/SIO), USGS Pasadena and USGS Menlo Park, the BSL is now streaming real time 1 Hz continuous data from over 40 sites, including all BSL sites and the 13 PBO stations in Parkfield, to the BSL, where it makes the data available to researchers in real time through an Ntripcaster.

The NCEDC also archives non-continuous survey GPS data. The initial dataset 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.

Geysers Seismic Data

The monitoring network for micro-seismicity in the Geysers region in Northern California was initially installed and operated by Unocal Geothermal Division, and later operated by Calpine Corporation. Through various agreements, both Unocal and Calpine have released triggered event waveform data from 1989 through 2000 along with preliminary event catalogs for the same time period for archiving and distribution through the NCEDC. This dataset represents over 296,000 events recorded by the Calpine/Unocal Geysers network, and is available as an assembled dataset at the NCEDC.

In late 2002, the Lawrence Berkeley National Laboratory (LBNL), with funding from the California Energy Commission, began installing a digital seismic network in the Geysers, and currently operates 33 stations in the Geysers region with an emphasis on monitoring seismicity related to well water injection. Initially, earthquake locations and event waveforms from this network were sent to the NCEDC, and the locations were forwarded to the NCSN so that they could be merged into the NCSN earthquake catalog. In August 2007, the NCSN installed an Earthworm system at The Geysers that received continuous waveform data from the LBNL Geysers network. The Earthworm system supplies the appropriate waveforms for events detected by the NCEMC real time earthquake monitoring and processing system and these waveforms are included in the pre-assembled event data archive at the NCEDC. In March 2012, the NCEDC started to receive and archive continuous data from the stations in near real-time for time-dependent velocity studies.

DOE Enhanced Geothermal Monitoring (EGS) Data

Starting in 2010–2011, LBNL funded the BSL to archive and disseminate seismic event parameters and corresponding waveform time series from monitoring networks operated under the auspices of the US Department of Energy Geothermal Monitoring Program. This includes the LBNL network installed at The Geysers. We have collected and verified the station metadata for these networks, and populated the data into the database. In 2012–2013 we began to receive and archive the event data and waveforms from these networks. The time series data are available via our suite of data delivery methods, and the event and parametric information are available via a new web catalog search page.

In 2013–2014 we started receiving the backlog of Geysers event waveforms starting in April 2003. As of June 2014, we have over 378,000 events, corresponding phase data, and time series data for the the EGS catalog. Although many of the events in the Geysers region are also included in the NCSS event catalog, the EGS catalog is maintained as a separate catalog for uniformity in event detection and location procedures.

The NCEDC also plans to include any appropriate EGS Geysers waveform data with the pre-assembled waveform set for any corresponding NCSS event from April 2003 to August 2007.

USGS Low Frequency Data

Starting in 1974, the USGS at Menlo Park, in collaboration with other principal investigators, collected an extensive low-frequency geophysical data set that contains over 1300 channels of tilt, tensor strain, dilatational strain, creep, magnetic field, and water level as well as auxiliary channels such as temperature, pore pressure, rain and snow accumulation, and wind speed. In collaboration with the USGS Menlo Park, 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 converting it to mini-SEED format. Since these data are delivered to the NCEDC on a daily basis and immediately archived, these data are not inserted into the NCEDC DART.

We have currently archived time series 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.

In 2011–2012 the USGS significantly reduced support for these stations, and most stations have been shut down. The last data delivered to the NCEDC for this network was in Feb 2013.

SCSN/Statewide Seismic Data

In 2004, the NCEDC started to archive broadband and strong motion data from 15 Southern California Seismic Network (SCSN) stations that were telemetered to the NCEMC. These data were used in the prototype real-time state-wide earthquake processing system and also provide increased coverage for Northern California events. Since the data are telemetered directly from the stations in real time to both the SCSN and to the NCEMC, the NCEDC archives the NCEMC's copy of the data to ensure that at least one copy of the data will be preserved. Due to reduced state funding, the SCSN has gradually reduced the number of telemetered stations to seven.

In early 2006, the NCEDC started to continuously archive all of the selected SCSN short period stations that are contributed to the NCSN. All of these data are also available in real time from the NCEDC DART. In 2009, the NCEMC started incorporating data from ~25 additional SCSN stations near the southern border of the NCEMC monitoring area in its event waveform collection to provide better azimuthal coverage of events in that area. In 2009–2010, the NCEMC also started retrieving event waveform data from the SCSN for other SCSN stations that are expected to receive signals from Northern California earthquakes. All of these event waveforms are also archived at the NCEDC.

Earthquake Catalogs

The NCEDC hosts multiple earthquake catalogs.

Northern California catalog: The NCEDC provides searchable access to both the USGS and BSL earthquake catalogs for Northern and Central California. The "official" UC Berkeley earthquake catalog begins in 1910 and runs through 2003, and the "official" USGS catalog begins in 1966. Both of these catalogs are archived and available through the NCEDC, but the existence of two catalogs has caused confusion among both researchers and the public.

In late 2006, the NCEMC began archiving and distributing a single unified Northern California earthquake catalog in real time to the NCEDC through database replication from the NCEMC's real-time systems. The NCEDC developed and tested the required programs used to enter all previous NCSN catalog data into the NCEDC database. In 2008, we migrated all of the historic NCSN catalog, phase, and amplitude data from 1967 through 2006 into the NCEMC catalog. In addition, we spent a considerable effort addressing the mapping of phase data in the BSL catalog to SEED channel names. We plan to merge the BSL catalog with the NCEMC catalog to form a single unified Northern California catalog from 1910 to the present. The BSL and the USGS have also spent a considerable effort over the past years 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.

Enhanced Geothermal Systems (EGS) catalog: The US Department of Energy Geothermal Monitoring Program is operating a number of seismic networks that monitor earthquakes in the regions of enhanced geothermal systems. The event catalogs and parametric information are available via a new EGS catalog search page.

Worldwide catalog: The NCEDC, in conjunction with the Council of the National Seismic System (CNSS) in the 1990s, produced and distributed a world-wide composite catalog of earthquakes based on the catalogs of the national and various U.S. regional networks. 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 for bulk download by anyone on the internet.

With the disbanding of the CNSS and the development of the Advanced National Seismic System (ANSS), the NCEDC was asked to update its web pages to present the composite catalog as a product of the ANSS. This conversion was completed in the fall of 2002. The NCEDC continues to create, house, distribute, and provide a searchable Web interface to this ANSS composite catalog, and to aid the regional networks in submitting data to the catalog. The ANSS is currently developing a new ANSS Combined Catalog (ComCat) which, when fully populated with historical events, may replace the current NCEDC's ANSS composite catalog.

The BSL made significant progress on data submission to the new ANSS ComCat using the new Product Distribution Layer (PDL), and provided timely feedback to the USGS Earthquake Hazards (EHZ) development team on both PDL and QuakeML issues. In 2012–2013, the BSL developed a flexible XML writer for AQMS systems that can generate QuakeML for any or all of the following PDL products:

1. Origin products (hypocenter and magnitudes)
2. Phase products (hypocenter, magnitudes, phase, and amplitudes readings)
3. Mechanism products (mechanism information with related gif images)
4. Moment tensor products (moment tensor information with related gif images).

The BSL has provided the AQMS QuakeML writer to all ANSS AQMS operators, and the NCSS is using it to generate real-time and reviewed Origin, Phase, Mechanism and Moment Tensor that are submitted to ComCat.

NCEDC Operations

The current NCEDC facilities consist of a mass storage environment hosted by an eight-core Sun X4150 computer, a 150 slot LTO5 tape library with three tape drives, and 180+ TBytes of RAID storage, all managed with the SAMFS hierarchical storage management (HSM) software. Four additional eight-core Sun computers host the DART data import, data archiving, computing Probability Density Function (PDF) plots for the bulk of the NCEMC waveforms, data quality control procedures, and internet distribution. Two 64-bit Linux systems host redundant Oracle databases used by the NCSS and NCEDC.

In 2005, the NCEDC relocated its archive and distribution system from McCone Hall to a new state-of-the-art campus data center in a new seismically braced building on the Berkeley campus. The facility provides seismically braced equipment racks, gigabit Ethernet network, air conditioning, and power conditioning. The data center is powered by UPS with generator backup.

The SAMFS HSM software used by the NCEDC is configured to automatically create multiple copies of each data file in the archive. The NCEDC creates one copy of each file on an online RAID, a second copy on LTO tape which remains online in the tape library, and a third copy on LTO tape which is stored offline and offsite. In addition, all NCEDC SAMFS data are cached in an online disk cache that provides instant access to these data. In 2011-2012, we renewed our SAMFS license, which now allows us to manage an unlimited amount of storage.

The NCEDC operates two instances of its Oracle database, one for internal operations and one for external use for user data queries and data distribution programs, and communicates with a third identical database operated offsite by the USGS in Menlo Park. These three databases are synchronized using multi-master replication.

DART (Data Available in Real Time)

The DART (Data Available in Real Time) provides a network-accessible structured file system to support real-time access to current and recent time series data from all networks, stations, and channels. All real-time time series data streams delivered to the NCEDC are placed in miniSEED files in a web accessible directory structure. The DART currently contains the most recent 40 days of data. Data from the DART is available to users through NCEDC web services and other data services described in the data distribution section of this chapter, and directly through web browsers and command-line programs such as *wget*.

We use the IRIS ringserver software as the primary method for delivering real time data to the DART. The ringserver packages implement an object ring buffer (ORB) and server, which provides a reliable storage ring buffer and an interface for client programs to read, write, and query the server. Clients running at the NCEDC computer connect to remote servers at the BSL, USGS Menlo Park, and other sites, retrieve the miniSEED time series data records, and write them to daily channel files in the NCEDC DART.

The NCEDC developed an automated data archiving system to archive data from the DART on a daily basis. It allows us to specify which stations should be automatically archived, and which stations should be handled by the NCEDC's Quality Control program, *calqc*. The majority of non-BSL data channels are currently archived automatically from the DART.

Data Quality Control

The NCEDC developed the GUI-based state-driven system *calqc* to facilitate the quality control processing that is applied to the BSL stations continuously archived data sets at the NCEDC.

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

- data extraction of a full day of data,
- a quickcheck program to summarize the quality and stability of the stations' clocks,
- determination if there is missing data for any data

channel,

- provided procedures to retrieve missing data from the stations and incorporate it into the day's data,
- optional creation of multi-day time series 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 is used to process all data from the BDSN and HRSN network, and all continuous broadband data from the NCSN, UNR, and SCSN networks that are archived by the NCEDC. The remainder of the continuously archived data are automatically archived without any analyst interaction.

Database Activity

The NCEDC continues to support the Northern California Earthquake Management Center (NCEMC) by providing information and resources vital to the NCEMC's role of rapid earthquake analysis and data dissemination. The NCEDC receives earthquake parametric data in real time from the NCEMC real-time systems and provides real-time access to the NCEDC database for *jiggle*, the CISN event analysis tool. The NCEMC continues to support the maintenance and distribution of the hardware configurations and instrument responses of the UCB, USGS Menlo Park NCSN, and other seismic stations used by the NCEMC. BSL staff currently chair the CISN Schema Change working group, which coordinates all database schema changes and enhancements within the CISN.

The NCEDC instrument response schema represents full multi-stage instrument responses (including filter coefficients) for the broadband data loggers. The hardware tracking schema represents the interconnection of instruments, amplifiers, filters, and data loggers over time, and is used to describe all of the UC Berkeley and USGS stations and channels archived at the NCEDC.

Database developments in the 2013–2014 year include support for preferred origin information for multiple types of location algorithms. This allowed us to add double-difference locations for events in addition to the current single event travel-time locations computed by hypoinverse. We are now effectively store multiple earthquake catalogs in the same database based on the location method. We allows users to select and search the desired catalog based on a consistent earthquake location methodology.

Full details on the database schema used at the NCEDC may be found at http://www.ncedc.org/db.

Data Distribution

The NCEDC continues to use the internet as the interface for users to request, search for, and receive data from the NCEDC. In fall 2005, the NCEDC acquired and began using the domain name ncedc.org. Information about the NCEDC, it's data sets and networks, and catalog search forms are located at http://www.ncedc.org. The NCEDC Web Services are available at the new web site http:/service.ncedc.org.

Earthquake Catalogs

The NCEDC provides users with searchable access to Northern California earthquake catalogs, the DOE EGS catalogs, and the ANSS world-wide catalog via the Web. Users can search the catalogs by time, magnitude, and geographic region, and can retrieve either hypocenter and magnitude information or a full set of earthquake parameters including phase readings, amplitudes, and codas. Moment tensor, first motion mechanisms, and the option of double different locations have been added to the NCEMC California earthquake catalog and are searchable from the NCEDC Web catalog search page.

Station Metadata

In addition to the metadata returned through the various data request methods, the NCEDC provides dataless SEED volumes and SEED RESP files for all data channels archived at the NCEDC. The NCEDC currently has full SEED instrument responses for 27,343 data channels from 3,185 stations in 24 networks. This includes stations from the California Geological Survey (CGS) strong motion network that will contribute seismic waveform data for significant earthquakes to the NCEDC and SCEDC, stations in the EGS networks, and strong motions stations in the USGS National Strong Motion Program (NSMP). In collaboration with the USGS, NCSN, and the NSMP (National Strong Motion Program), the NCEDC constructed the metadata and dataless SEED volumes for over 700 stations and 4700 data channels of the NSMP dialup stations. Station metadata can be acquired from fdsnws station or by downloading pre-assembled dataless SEED files, using *ncedc-dataless* web service or NetDC to request metadata by station, channel and time.

NCEDC Website Upgrade

This year, the front end of the NCEDC web site was upgraded. While BSL programmers have steadily pushed out new tools for researchers to use in acquiring data as well as maintaining existing tools, the web page itself had been suffering from a lack of attention. The existing site was previously updated circa 2003 by seismologist Lind Gee, and the structure and content were poorly maintained upon her departure, resulting in a difficult to navigate maze of pages with repeated and in some cases out of date content.

We performed a content inventory of the pages, drafted a new menu structure, and iterated with the data center manager Doug Neuhauser and a team of BSL seismologists until a sensible menu scheme emerged. We also worked with partner agencies to create updated content about our networks for the network description pages. The new look and feel was adapted from the upgraded BSL site to reflect the close association between the NCEDC and BSL while acknowledging our partner agencies. We also implemented an NCEDC email list signup form. Future work on the NCEDC page's front end will include creation of an NCEDC blog and removal of no-longer-needed pages.

Web Services

The NCEDC has developed and deployed web services for distributing time series data, related channel metadata, and event catalog data. Web services use standard web HTTP protocol for sending requests and receiving data. Web services can be used interactively from a web browser, from scripts, and directly from user-written programs and libraries such as python or matlab. Whenever possible the *ncedcws* web services are compatible with the corresponding IRIS DMC *irisws* web services of the same name. The currently supported data services are:

- *ncedc-sacpz*—provide poles and zeros for the specified channels and time interval in SAC ASCII format.
- *ncedc-resp*—provide response information for the specified channels and time intervael in RESP format.
- *ncedc-dataless*—provide station information and channel response in FDSN dataless SEED format.
- *ncedc-eventdata*—provides time series data from pre-assembled collection of waveforms identified by the specified earthquake catalog and eventid.

In order to encourage standards for data delivery from data centers, in 2012 the International Federation of Digital Seismograph Networks (FDSN) defined specifications for three web services that could provide earthquake catalog information, station and channel metadata, and time series data. In 2013, the NCEDC developed and deployed production web services for each of the FDSN-defined web services, and retired older web services that FDSN services replaced.

- *fdsn-dataselect*—returns one or more channel of time series data in miniSEED format for specified time ranges.
- *fdsnws-station*—provides station and channel metadata and optional time series availability in StationXML format.
- *fdsnws-event*—provides earthquake catalog information in QuakeML format.

The *fdsnws-dataselect* service now delivers time series data seamlessly merged from the NCEDC archive and NCEDC DART. This provides users a single request method that can deliver both current and historic time series.

FDSN StationXML is an XML (Extensible Markup Language) schema for representing station and channel metadata. StationXML was originally designed at the SCEDC and later adopted by the FDSN. RESP format is the ASCII channel response format created by the IRIS *rdseed* program, and supported by programs such as *evalresp*. Documentation on FDSN Station XML is available at http://www.fdsn.org/xml/station/.

SeismiQuery

The NCEDC ported and installed the IRIS *SeismiQuery* program at the NCEDC, which provides a web interface to query network, station, and channel attributes and query the availability of archived time series data.

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. *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 operated at several datacenters worldwide, including NCEDC, IRIS DMC, ORFEUS, Geoscope, and SCEDC. 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 IRIS DMC deprecated NetDC in 2012, but the NCEDC continues to support NetDC data, inventory, and metadata requests.

STP

In 2002, 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 simple client-server program, developed at the SCEDC. Access to *STP* is either through a simple direct interface that is available for Sun or Linux platforms, or through a GUI Web interface. With the direct interface, the data are placed directly on a user's 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 continued work on *STP*, working with the SCEDC on extensions and needed additions. We added support for the full SEED channel name (Station, Network, Channel, and Location), and are now able to return event associated waveforms from the NCSN waveform archive.

EVT_FAST

In order to provide Web access to the NCSN waveforms before the SEED conversion and instrument response for the NCSN has been completed, the NCEDC implemented *EVT_FAST*, an interim email-based waveform request system similar to the *BREQ_FAST* email request system. Users email *EVT_FAST* requests to the NCEDC and request NCSN waveform data based on the NCSN event ID. *EVT_FAST* event waveforms can be delivered in either miniSEED or SAC format, and are now named with their SEED channel names.

FISSURES

The *FISSURES* project developed from an initiative by IRIS to improve earth scientists' efficiency by developing a unified environment that can provide interactive or programmatic access to waveform data and the corresponding metadata for instrument response, as well as station and channel inventory information. *FISSURES* was developed using CORBA (Common Object Request Broker Architecture) as the architecture to implement a system-independent method for the exchange of this binary data. The IRIS DMC developed a series of services, referred to as the *Data Handling Interface (DHI)*, using the *FISSURES* architecture to provide waveform and metadata from the IRIS DMC.

The NCEDC has implemented the *FISSURES Data Handling Interface (DHI)* services at the NCEDC, which involves interfacing the DHI servers with the NCEDC database schema. These services interact with the NCEDC database and data storage system and can deliver NCEDC channel metadata as well as waveforms using the *FISSURES* interfaces. We have separate *FISSURES DHI* waveform servers to serve archived and DART data streams. Our *FISSURES* servers are registered with the IRIS *FISSURES naming services*, which ensures that all *FISSURES* users have transparent access to data from the NCEDC.

The IRIS DMC deprecated its support for FISSURES in 2012–2013, but the NCEDC continues to support all of its FISSURES servers and assumed responsibility for the FISSURES name service.

SWC and SWS

UC Berkeley developed the Simple Wave Server, *sws,* and Simple Wave Client, *swc,* programs to provide access to its miniSEED data from the DART and the NCEDC archive. It currently operates a separate server for each of the above services. The *swc* program is a command-line client program written in perl that runs under Linux, Unix, and MacOS and allows users to easily retrieve waveform data in miniSEED format by channel and time window or by NCEMC event gathers. The program is packaged for easy user installation and can be downloaded from the NCEDC web site.

The NCEDC operates two distinct SWS services. The *ncedc_archive* service provides access to data that has been formally archived at the NCEDC, and the *dart* service provides access to real time data from the DART.

GPS

GPS data (raw data, RINEX data at 15 second interval, and high-rate 1 Hz RINEX data) are all available via HTTP or FTP over the internet in a well-defined directory structure organized by data type, year, and day-of-year.

Metrics for 2013–2014

- NCEDC uptime for data delivery was over 99.9% for the year.
- Tables 4.8.2 and 4.8.3 provide a breakdown by network or type of data of the total NCEDC archive size, statistics about this fiscal year's waveform archive after QC work, statistics for month of data without QC, and data distribution information for the fiscal year.

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Network	Total Archive Size (GB)	2013-14 % of Waveform Data Archived	Avg # of Waveform Segments	Avg Segment Length (days)	% of Stations with <= 12 Segments
BG	3,837.55	98.67%	714	15.16	0%
BK	13,018.89	99.23%	26	246.85	75%
BP	5,004.54	98.28%	95	149.48	50%
CE	102.42	99.20%	146	17.99	0%
CI	3,762.78	85.93%	1030	22.69	13%
NC	30,330.59	95.83%	728	27.22	2%
NN	2,795.98	98.89%	520	28.43	8%
NP	6,394.37	n/a	n/a	n/a	n/a
PB	4,945.03	n/a	n/a	n/a	n/a
PG	1,433.39	90.84%	280	13.56	0%
SF	527.49	99.22%	181	8.89	0%
TA	656.34	96.56%	175	64.20	0%
UL	0.45	n/a	n/a	n/a	n/a
US	2.91	n/a	n/a	n/a	n/a
WR	1,396.79	79.25%	2229	6.20	0%
Other Net	n/a	n/a	n/a	n/a	n/a
NCSS events	1,306.81	n/a	n/a	n/a	n/a
EGS events	497.24	n/a	n/a	n/a	n/a
Subtotal	76,013.59				
GPS Data	4,559.71	n/a	n/a	n/a	n/a
Other Data	1,484.23	n/a	n/a	n/a	n/a
Catalog Data	n/a	n/a	n/a	n/a	n/a
Total	82,057.53				

Table 4.8.2: Total NCEDC archive broken down by continuous waveforms from seismic networks, event waveforms for different catalogs, GPS data, and other data sets for the year 2013–2014. Each network is broken down into the percentage of possible waveforms actually archived, the average number of distinct continuous waveform segments, the average lengthof waveform segments in days, and the percentage of stations that have fewer than12 continuous segments per year. A perfect complete waveform archive would be represented by 100% data return, average segment length of 365 days, and 100% of stations with ≤12 segments.

Network	June 2014 % of Waveform Data Archived	Avg # of Waveform Segments	Avg Segment Length (days)	% of Stations with 1 Segment	Data Distributed (GB) this year	Unique Users this year
BG	99.98%	127	7.53	0%	1,846.77	129
BK	96.54%	11	27.10	67%	1,023.16	510
BP	97.07%	6	26.50	67%	781.02	92
CE	100.00%	12	7.20	0%	0.47	31
CI	87.69%	92	7.12	23%	8.19	81
NC	95.49%	1169	5.51	0%	669.80	176
NN	99.19%	83	8.62	0%	16.60	52
NP	91.73%	143	8.36	0%	3.65	46
PB	99.53%	3	21.70	42%	23.49	96
PG	81.25%	41	4.26	0%	24.44	47
SF	76.31%	19	5.86	0%	5.88	54
TA	n/a	n/a	n/a	n/a	1.68	33
UL	n/a	n/a	n/a	n/a	0.01	1
US	n/a	n/a	n/a	n/a	0.09	25
WR	83.18%	4365	3.09	0%	2.25	18
Other Net	n/a	n/a	n/a	n/a	0.33	37
NCSS events	n/a	n/a	n/a	n/a		
EGS events	n/a	n/a	n/a	n/a		
Subtotal					4,407.83	745
GPS Data	n/a	n/a	n/a	n/a	303.06	269
Other Data	n/a	n/a	n/a	n/a	36.58	264
Catalog Data	n/a	n/a	n/a	n/a	22,846.76	8468
Total					27,594.22	9626

Table 4.8.3: This table shows the same statistics as Table 4.8.2. The first column shows the percent of June 2014 data real-time waveform stored in the NCEDC DART. This represents data transmitted in real-time or near-real time to the NCEDC, and includes no data backfilling from QC (quality control) processes. In addition, the table shows the total data distributed by network and other data sets during the reporting year, and the number of distinct users of each network or data set.

Glossary of Common Acronyms

Acronym	Definition
ADA	Amplitude Data Area
ANSS	Advanced National Seismic System
ANSS NIC	ANSS National Implementation Committee
AQMS	ANSS Quake Monitoring System
ARRA	American Recovery and Reinvestment Act
BARD	Bay Area Regional Deformation
BAVU	Bay Area Velocity Unification
BDSN	Berkeley Digital Seismic Network
BSL	Berkeley Seismological Laboratory
CalEMA	California Emergency Management Agency
Caltrans	California Department of Transportation
CDF	California Department of Forestry
CGS	California Geological Survey
CISN	California Integrated Seismic Network
DART	Data Available in Real Time
EEW	Earthquake Early Warning
ElarmS	Earthquake Alarm Systems
EM	Electromagnetic
FACES	FlexArray along Cascadia Experiment for Segmentation
FEMA	Federal Emergency Management Agency
HFN	Hayward Fault Network
HRSN	High Resolution Seismic Network
InSAR	Interferometric Synthetic Aperture Radar
IRIS	Incorporated Research Institutions in Seismology
IRIS DMC	IRIS Data Management Center
LBNL	Lawrence Berkeley National Laboratory
LFE	Low Frequency Event
LLNL	Lawrence Livermore National Laboratory
MARS	Monterey Accelerated Research System
MBARI	Monterey Bay Aquarium Research Institute
MOBB	Monterey Ocean Bottom Broadband Observatory
mPBO	Mini-Plate Boundary Observatory
MT	Magnetotelluric
MT	Moment Tensor
MTJ	Mendocino Triple Junction
NCEDC	Northern California Earthquake Data Center
NCEMC	Northern California Earthquake Management Center
NCSN	Northern California Seismic Network
NCSS	Northern California Seismic System
NHFN	Northern Hayward Fault Network

Continued on next page

NVT	Non-volcanic Tremor
PBO	Plate Boundary Observatory
PDF	Probability Density Function
PGV	Peak Ground Velocity
PSD	Power Spectral Density
QDDS/EIDS	Quake Data Distribution System/Earthquake Information Distribution System
REDI	Rapid Earthquake Data Integration
RES	Repeating Earthquake Sequence
SAF	San Andreas Fault
SAFOD	San Andreas Fault Observatory at Depth
SCSN	Southern California Seismic Network
SEED	Standard for Exchange of Earthquake Data
SEM	Spectral Element Method
SHFN	Southern Hayward Fault Network
SOH	State of Health
SSE	Slow Slip Event
UNACO	University NAVSTAR Consortium
USGS/MP	United States Geological Survey/ Menlo Park
USNSN	United States National Seismic Network

Appendix I: Publications, Presentations, Awards and Panels

Publications

Amos, C. B., S. J. Brownlee, D. H. Rood, G. B. Fisher, R. Bürgmann, P. R. Renne, and A. S. Jayko, Chronology of tectonic, geomorphic, and volcanic interactions and the tempo of fault slip near Little Lake, California, *Geological Society of America Bulletin*, 125(7-8), doi: 10.1130/B30803.30801, 2013.

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Allen, R.M., Scientific Briefing for Suzette Kimball, Acting Director, U.S. Geological Survey, Berkeley, California, July 18, 2013.

Allen, R.M., Earthquake early warning: Now, or after the next big quake?, Palm Springs, California, September 11, 2013.

Allen, R.M., Warning California: Extracting earthquake signals from noise before the shaking starts, UC Berkeley Data Science Lecture Series, Berkeley, California, September 27, 2013.

Allen, R.M., Earthquake early warning for the US West Coast: Status and new opportunities, Zürich, Switzerland, October 23, 2013.

Allen, R.M., Earthquake early warning: New science and technology to mitigate earthquakes, Rio de Janeiro, Brazil, November 16, 2013.

Allen, R.M., MyShake: Smartphone seismic networks, Hoover Institution, Stanford University, California, December 4-5, 2013.

Allen, R.M., Scientific briefing for Advisors for U.S. Senator Feinstein and Representatives Schiff and Calvert,Washington DC, January 8, 2014.

Allen, R.M., Warning California: Science and technology to reduce the growing earthquake threat, American Society of Home Inspectors, Golden Gate Chapter, Berkeley, California, February 13, 2014.

Allen, R.M., Earthquake Alert: Harnessing BIG data to satisfy societal needs and facilitate new science, Earth Science Colloquium, Lamont-Doherty Earth Observatory, Columbia University, New York, February 21, 2014.

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Allen, R.M., Earthquake Alert: Harnessing BIG data to satisfy societal needs and facilitate new science, Yuval Ne'eman Distinguished Lectures in Geophysics, Atmosphere and Space Sciences, Tel Aviv University, Israel, March 31, 2014.

Allen, R.M., Imaging the origin of hotspots and the fate of slabs, Yuval Ne'eman Distinguished Lectures in Geophysics, Atmosphere and Space Sciences, Tel Aviv University, Israel, April 2, 2014.

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Allen, R.M., MyShake: Smartphone seismic networks. Intelligence Challenges Workshop, Hoover Institution, Stanford University, California. May 15, 2014.

Allen, R.M., CISN ShakeAlert, Cal Maritime, Vallejo, California. May 19, 2014.

Allen, R.M., Warning California: The day the earthquake comes, SwissNex Hackathon on earthquake resilience, San Francisco, California, May 31, 2014.

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Allen, R.M., Testimony to the United States House of Representatives, Committee on Natural Resources, Subcommittee on Energy and Mineral Resources. Oversight hearing on "Whole Lotta Shakin: An Examination of America's Earthquake Early Warning System Development and Implementation." Washington, DC, June 10, 2014.

Allen, R.M., Scientific briefing for Advisors for U.S. Representatives Schiff, Lee, Honda, Chu and Swalwell, Washington DC, June 10 and 17, 2014.

Bodin, Thomas, Trandimensional Inference in Geosciences ,Lawrence Berkeley National Laboratory (LBNL), May 16, 2014.

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Bürgmann, R., Megathrust Earthquake Cycles, 2013 Birch Lecture, Tectonophysics Section of American Geophysical Union, 2013 Fall Meeting, December 10, 2013.

Bürgmann, R., Periodic Deformation and Seismicity: From Tides to Seasonal Water Loads, Department of Earth Sciences, University of Southern California, May 5, 2014.

Bürgmann, R., Periodic Deformation and Seismicity: From Tides to Seasonal Water Loads, USGS Western Region Colloquium, June 9, 2014.

Bürgmann, R. and R.M. Nadeau (Invited), Briefing on the Borehole High-Resolution Seismic Network (HRSN) at Parkfield, CA and its Associated Research and Monitoring, Meeting of the National Earthquake Prediction Evaluation Council (NEPEC) for Review of the State of Research and Monitoring Work Around Parkfield, California, USGS Menlo Park, Menlo Park, CA, November 4-5, 2013.

Calò M., Fluid-related induced seismicity and Enhanced Geothermal fields. Insights from the 4D seismic tomography, UC Berkeley, Berkeley Seismological Laboratory Seminar, February 4, 2014.

Calò M., Induced Seismicity and Geothermal Fields. Constraints from 4D seismic tomography on the fault-fluid interaction, University of Santa Cruz, IGPP, California, February 7, 2014.

Calò M., Use of the induced seismicity and seismic noise correlation tomography for improving exploration and optimization of geothermal fields, Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico, May 14, 2014.

Chaussard, E., Characterization of geohazards at regional scales using space geodesy: examples of land subsidence and volcanic eruptions, Berkeley Seismological Laboratory Seminar, Berkeley, CA, October 1, 2013.

Chaussard, E., Remote sensing of ground deformation: an indispensable tool for groundwater resources and hazards management, Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences Special Seminar, May 22, 2014.

Delbridge, B., B. Buffett, S. Kita, T. Matsuzawa, Application of thin sheet dynamics to subduction zones: Implications for lithospheric rheology, seismogenesis and estimates of bending dissipation, International Summer School on Earthquake Science.

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Grapenthin, R., Plumbing, Plumes, and Early Warning: Using GPS near Volcanoes, Department Seminar, DTM ,Carnegie Institution for Science, Stanford, CA, March 11, 2014.

Grapenthin, R., Plumbing, Plumes, and Early Warning: Using GPS near Volcanoes, Department Seminar, South Dakota School of Mines and Technology, Rapid City, SD, February 18, 2014.

Grapenthin, R., Plumbing, Plumes, and Early Warning: Using GPS near Volcanoes, Department Seminar, New Mexico Tech, Socorro, NM, January 30, 2014.

Grapenthin, R., Kinematic GPS and Earthquakes: From a Single Time Series to Early Warning, Active Tectonics guest lecture, Cornell University, Ithaca, NY, October 16, 2013.

Grapenthin, R., Plumbing, Plumes, and Early Warning: Using GPS near Volcanoes, Department Seminar, Cornell University, October 16, Ithaca, NY, 2013.

French, S., Toward a full-waveform radially anisotropic shear-velocity model of the earth's whole mantle, Lawrence Berkeley National Laboratory, Earth Sciences Division, Geophysics Seminar Series, January 30, 2014.

Hellweg, M., Earthquakes in our Backyard, Pt. Reyes National Monument, CA, September 26, 2013.

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Huang, M.-H., Probing the deep rheology across the eastern margin of the Tibetan Plateau: Constraints from the 2008 Mw 7.9 Wenchuan, China earthquake, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, January 28, 2014.

Johanson, I., The BARD network: Two Decades of Multi-scale Deformation Measurements in Northern California, California Spatial Reference Center Coordinating Council Semi-Annual Meeting, May 1, 2014.

Johanson, I., R. Grapenthin, P. Lombard, D. Dreger and R. Allen, High-rate GPS for Earthquake Early Warning and Rapid Response, Caltech Seismological Lab Seminar, March 14, 2014.

Romanowicz, B., Low velocities in the oceanic upper mantle and their relations to plumes: insights from SEM-based waveform tomography, CIG/QUEST joint workshop, Fairbanks, Alaska, July 17, 2013.

Romanowicz, B., Global Earth structure in the 21st century, Ettore Majorana Center, Erice, Sicily, August 31, 2013.

Romanowicz, B., Channeled flow at the base of the oceanic asthenosphere: evidence from full waveform tomography, Univ. of Uppsala, Sweden, September 12, 2013.

Romanowicz, B., Low velocity fingers in the oceanic upper mantle and their relations to plumes, IPG Paris, October 1, 2013.

Romanowicz, B., Subduction zones, mantle plumes and recent results from global waveform tomography, IPG Paris, Symposium in the honor of Renata Dmowska, October 14, 2013.

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Romanowicz, B., Voyage à l'Intérieur de la Terre, Bibliothèque Polonaise à Paris, France, November 27, 2013.

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Romanowicz, B., Imagi(ni)ng the Earth's Interior, Geological Society of Northern California, Orinda, CA, January 30, 2014.

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Romanowicz, B., Imagerie Sismique Globale du Manteau Terrestre par Inversion de Forme d'Onde: panaches mantelliques et convection à petite échelle?, University of Lyon, France, June 1, 2014.

Romanowicz, B., Science au féminin: réflexion sur le parcours d'une géophysicienne", Nuit des Science, ENS Ulm, June 6, 2014.

Strauss, J. A., Shaping Response and Recovery with Earthquake Early Warning, Business Recovery Managers Association, July 2013 Membership Meeting, Oakland, CA, July 25, 2013.

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Strauss, J. A., and R. M. Allen, Warning California: Science and technology to reduce the growing earthquake threat, San Francisco Planning and Urban Research Association, Lunchtime Forum, San Francisco, CA, October 31, 2013.

Taira, T., Seismic Constraints on Fault-Zone Rheology at Depth from Characteristically Repeating Earthquakes at Parkfield, California, Solid Earth group seminar, University of Tokyo, Japan, July 4, 2013.

Taira, T., Investigating transient slip behavior and fault frictional properties from repeating microearthquake activity along the San Andreas fault in the San Juan Bautista region, the National Institute of Advanced Industrial Science and Technology, Japan, July 16, 2013.

Taira, T., On the Systematic Long Period Noise Reduction on Ocean Floor Broadband Seismic Sensors Collocated with Differential Pressure Gauges, Ocean Hemisphere Project group seminar, Earthquake Research Institute, Japan, July 19, 2013.

Taira, T., Investigating transient slip behavior and fault frictional properties from repeating microearthquake activity along the San Andreas fault in the San Juan Bautista region, Earthquake Research Institute Friday Seminar, Japan, July 25, 2013.

Taira, T., Seismic Constraints on Fault-Zone Strength and Rheology at Seismogenic Depth on the San Andreas Fault, Parkfield, Yokohama City University, Japan, July 29, 2013.

Taira, T., Seismic Constraints on Fault-Zone Strength and Rheology at Seismogenic Depth on the San Andreas Fault, Parkfield, Hot Springs Research Institute of Kanagawa Prefecture, Japan, July 31, 2013.

Taira, T., Investigating transient slip behavior and fault frictional properties from repeating microearthquake activity along the San Andreas fault in the San Juan Bautista region, Hokkaido University, Japan, August 7, 2013.

Taira, T., Borehole Seismic Monitoring of Deep Fault Deformation along the Hayward Fault, CA, Seismology Group Seminar, Ludwig-Maximilians-Universität München, Germany, November 19, 2013.

Awards

Taka'aki Taira

Best Young Scientist Poster Award, International Continental Scientific Drilling Program

Visiting Fellowship, Earthquake Research Institute, University of Tokyo, Japan

Barbara Romanowicz

Elected Member of the French Academy of Sciences

Panels and Professional Service

Richard M. Allen

Lead Organizer, 3rd International Conference on Earthquake Early Warning: Implementing Earthquake Alerts
Chair, U.S. Earthquake Early Warning Coordination Committee, February 2013–present
Chair, International Earthquake Early Warning Advisory Committee, Geological Institute of Israel, 2012-present
Member, Scientific Advisory Board, European Union Framework 6 Project: Strategies and Tools for Real Time Earthquake Risk Reduction (REAKT), 2011–present
Member, Cascadia Initiative Expedition Team, Responsible for deploying ocean-bottom instrumentation for the community-designed Cascadia Initiative funded by NSF, 2011–present
Chair, U.S. Earthquake Early Warning Scientific Coordination Committee, July 2006–present
Co-Organizer, 6th CIDER Summer Program: From mantle to crust: Continental formation and destruction

Roland Bürgmann

Associate Editor, Bulletin of the Seismological Society of America
Editorial Board, Earth and Planetary Science Letters
Member, Facilities Committee of DEFORM
Member, Membership Committee of UNAVCO
Member, National Earthquake Prediction Evaluation Council (NEPEC)
Member, Board of Directors of Southern California Earthquake Center (SCEC)
Member, Earth Science Subcommittee of NASA Advisory Council
Member, AGU Tectonophysics Union Fellows Committee
Co-Chair, IRIS Grand Challenge Science Advisory Committee

Douglas S. Dreger

Cosmos Board of Directors

Margaret Hellweg

Commissioner, Alfred E. Alquist Seismic Safety Commission
Member, CISN Program Management Committee
Member, CISN Standards Committee
Member, CISN Steering Committee
Member, CISN Outreach Committee
Member, ANSS Performance Standards Committee
Member, ANSS Depth Datum Working Group
Chair, CISN ShakeMap Working Group
Chair, ANSS Class C Instrumentation Evaluation Committee
Member, Bay Area Earthquake Alliance Committee
Member, Bay Area Earthquake Alliance Executive Committee
Member, Editorial Board of Journal of Volcanology and Geothermal Research
Member, New Media Committee, Seismological Society of America
Member, California Earthquake Early Warning System Standards Committee
Member, California Earthquake Early Warning System Charter Committee

Bob Nadeau

Member, Berkeley Institute for Data Sciences (BIDS)

Douglas S. Neuhauser

Chair, Standards Group, California Integrated Seismic Network (CISN)
Acting Member, CISN Program Management Committee

Barbara Romanowicz

Member, Conseil d'établissement, Collège de France
Member, advisory committee, COMPRES program
Chair, section 16, National Academy of Sciences (USA)
Chair, doctoral thesis committee, Scott French, UC Berkeley, May 2014
Chair, doctoral thesis committee,, Zhao Zheng, UC Berkeley, May 2014
Participation in the preparation of a "white paper" in the framework of the european program EPOS
Member, Science advisory committee, GEOSCOPE program
Selection committee member, Arthur Holmes Medal, European Geophysical Union.
Organization of post-AGU CIDER workshop, December 8, 2013, Berkeley
PI, Cooperative Institute for Dynamic Earth Research

Jennifer Strauss

Member, California Earthquake Early Warning Planning Committee
Member, California Earthquake Early Warning System Education and Training Committee
Chair, CISN Earthquake Early Warning Communications Committee
Participant, Lifelines Council, San Francisco
Participant, Rockefeller Foundation 100 Resilient Cities Agenda-Setting Workshop

Taka'aki Taira

Member, Editorial board for Solid Earth
Member, California Integrated Seismic Network, Standards Committee
Member, California Integrated Seismic Network, ShakeMap Working Group
Member, Plate Boundary Observatory, Data Working Group

Appendix II: Seminar Speakers

Norm Abrahamson
UC Berkeley
"Seismological Research that will have the largest effects on seismic hazard evaluations in California in the next 5-10 years."
September 3, 2013

Yan Hu
UC Berkeley
"Upper Mantle Rheology Constrained From Subduction Zone Earthquake Cycle Deformation and Post-Glacial Rebound."
September 10, 2013

Abhijit Ghosh
University of California, Riverside
"Slow earthquakes and tremor -- where are we headed?"
September 17, 2013

Charlie Sammis
University of Southern California
"The Role of Deep Creep in the Timing of Large Earthquakes."
September 24, 2013

Estelle Chaussard
UC Berkeley
"Characterization of geohazards at regional scales using space geodesy: examples of land subsidence and volcanic eruptions."
October 1, 2013

Lingseng Meng
UC Berkeley
"Application of Back Projection Imaging to Earthquake Early Warning and Deep-Focus Earthquakes."
October 8, 2013

Dave Stegman
UC San Diego
"The amazing story of Yellowstone-related volcanism."
October 15, 2013

Ken Hudnut
USGS
"UAVSAR Reveals Surface Faulting and GPS PPP(AR) Assists in Earthquake Early Warning."
October 22, 2013

Peter Shearer
University of California, San Diego
"Has the probability of big earthquakes recently increased?"
October 29, 2013

Fukashi Maeno
ERI, University of Tokyo
November 05, 2013

Tom Parsons
USGS
"The global aftershock zone."
November 12, 2013

Julian Lozos
UC Berkeley, PEER
"Rupture and Ground Motion Models on the Claremont - Casa Loma Stepover of the San Jacinto Fault, Incorporating Complex Fault Geometry, Stresses, and Velocity Structure."
November 19, 2013

Donna Eberhart-Phillips
University of California, Davis
"Imaging P and S Attenuation in the Termination Region of the Hikurangi Subduction Zone, New Zealand."
November 26, 2013

Jennifer Frederick
UC Berkeley
“Relict Arctic permafrost-associated gas hydrate deposits: Methane gas escape in response to warming due to natural climate variability.”
December 3, 2013

Emily Brodsky
University of California, Santa Cruz
“Stress on Faults..”
January 21, 2014

David Schmidt
University of Washington
“The interseismic accumulation and transient release of strain on the Cascadia Subduction Zone”
January 28, 2014

Marco Calo
UC Berkeley
“Fluid-related induced seismicity and Enhanced Geothermal fields. Insights from the 4D seismic tomography. .”
February 04, 2014

Thorsen Becker
University of Southern California
“Seismic anisotropy as a tool for understanding regional tectonics.“
February 18, 2014

James Badro
Institut de Physique du Globe Paris
“Accreting the Earth and Forming its Core: Experimental and Theoretical Constraints”
February 25, 2014

Eric Geist
USGS
“Tsunami Edge Waves: An Oceanic Analog to Love Waves.”
March 3, 2014

Michael Thorne
University of Utah
“Ultra-low velocity zones and deep mantle flow.”
March 11, 2014

Maxim Ballmer
University of Hawai’i, Manoa
“Long-term survival of compositional layering across the Transition Zone in the presence of whole-mantle convection .”
March 18, 2014

Heidi Houston
University of Washington
“Slow slip,tremor, and tidal stressing: Fault weakening during ETS.”
April 1, 2014

Yuning Fu
California Institute of Technology/JPL-NASA
“TGPS as a high resolution technique for estimating water storage variations in Washington, Oregon, and California.”
April 8, 2014

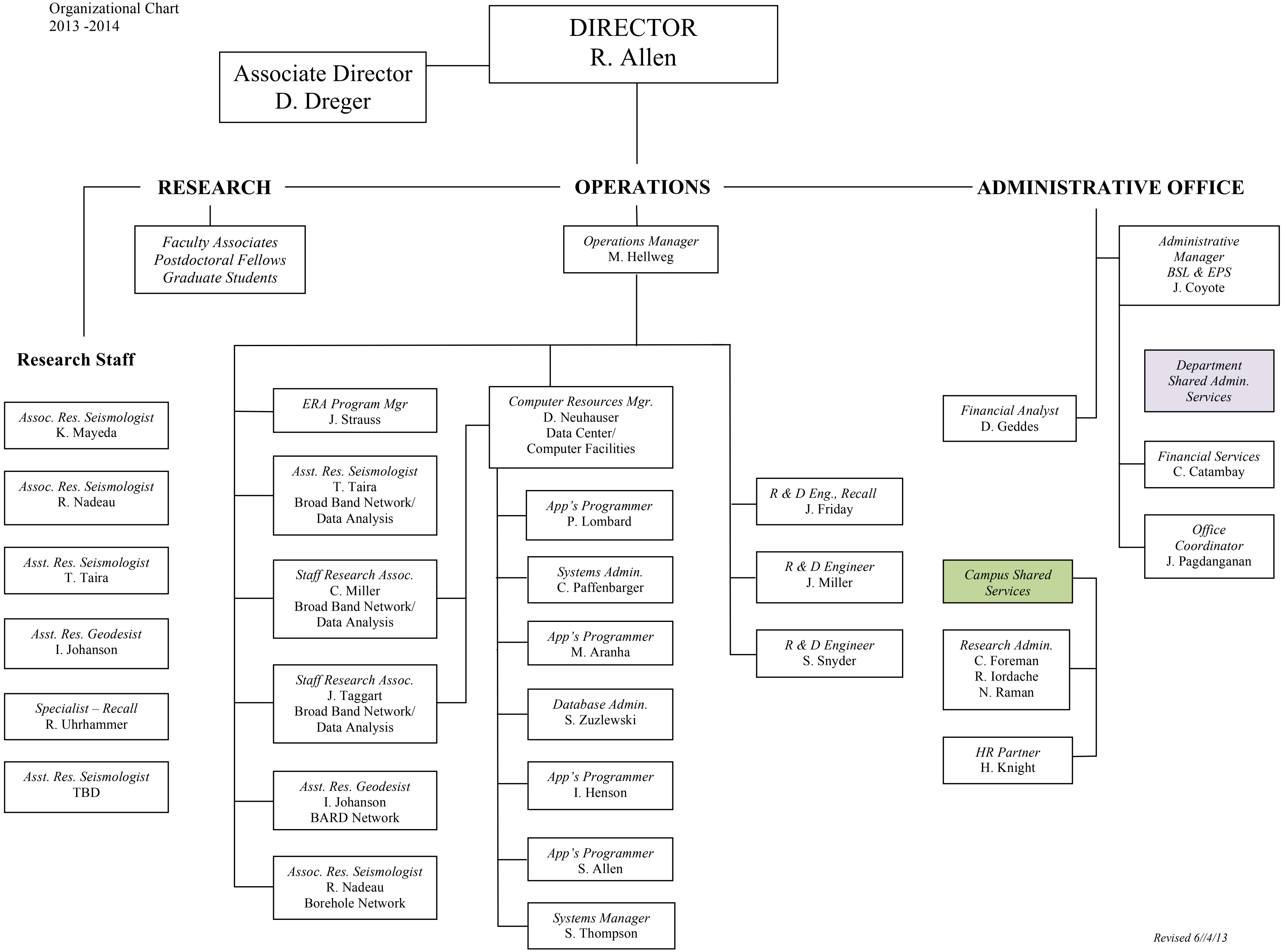
Anna Kelbert
Oregon State University
“High resolution global electrical conductivity variations in the Earth’s mantle.”
April 15, 2014

Scott French
UC Berkeley
“New Constraints on Whole-mantle Structure using Full-Waveform Tomography.”
April 22, 2014

Romain Jolivet
California Institute of Technology
“Bayesian exploration of the sources parameters of the 2013, Mw 7.7, Balouchistan earthquake.”
April 29, 2014

Zhao Zheng
UC Berkeley
“High resolution upper mantle discontinuity images across the Pacific from SS precursors ”
May 6, 2014

Berkeley Seismological Laboratory
Organizational Chart
2013 -2014



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