Chapter 3

BSL Operations

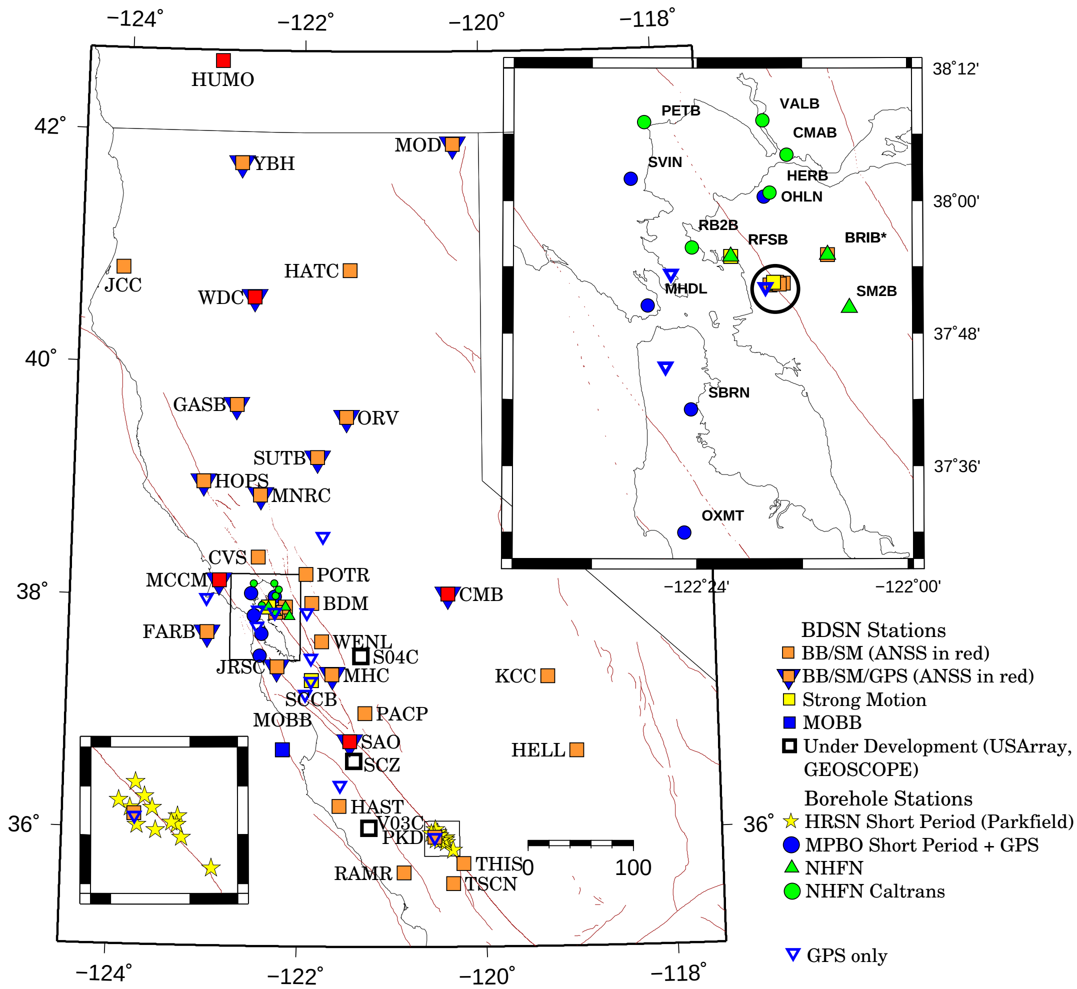

Figure 3.1: Map illustrating the distribution of BSL networks in Northern and Central California. USGS and CalEMA contribute to operating these stations. ANSS backbone stations are shown in red. In the upper right inset map, the shown stations in the circle include BRK, BKS, and CMSB on the Berkeley campus and VAK, BL88, and BL67 on the campus of the Lawrence Berkeley Lab. * Station BRIB is also a GPS and mPBO site. Boundaries for the lower left inset map are 120.65°- 120.2°West, 35.78°- 36.08°North. Abbreviations: BB/SM - Broadband/Strong Motion; BB/SM/GPS - Broadband/Strong Motion/GPS

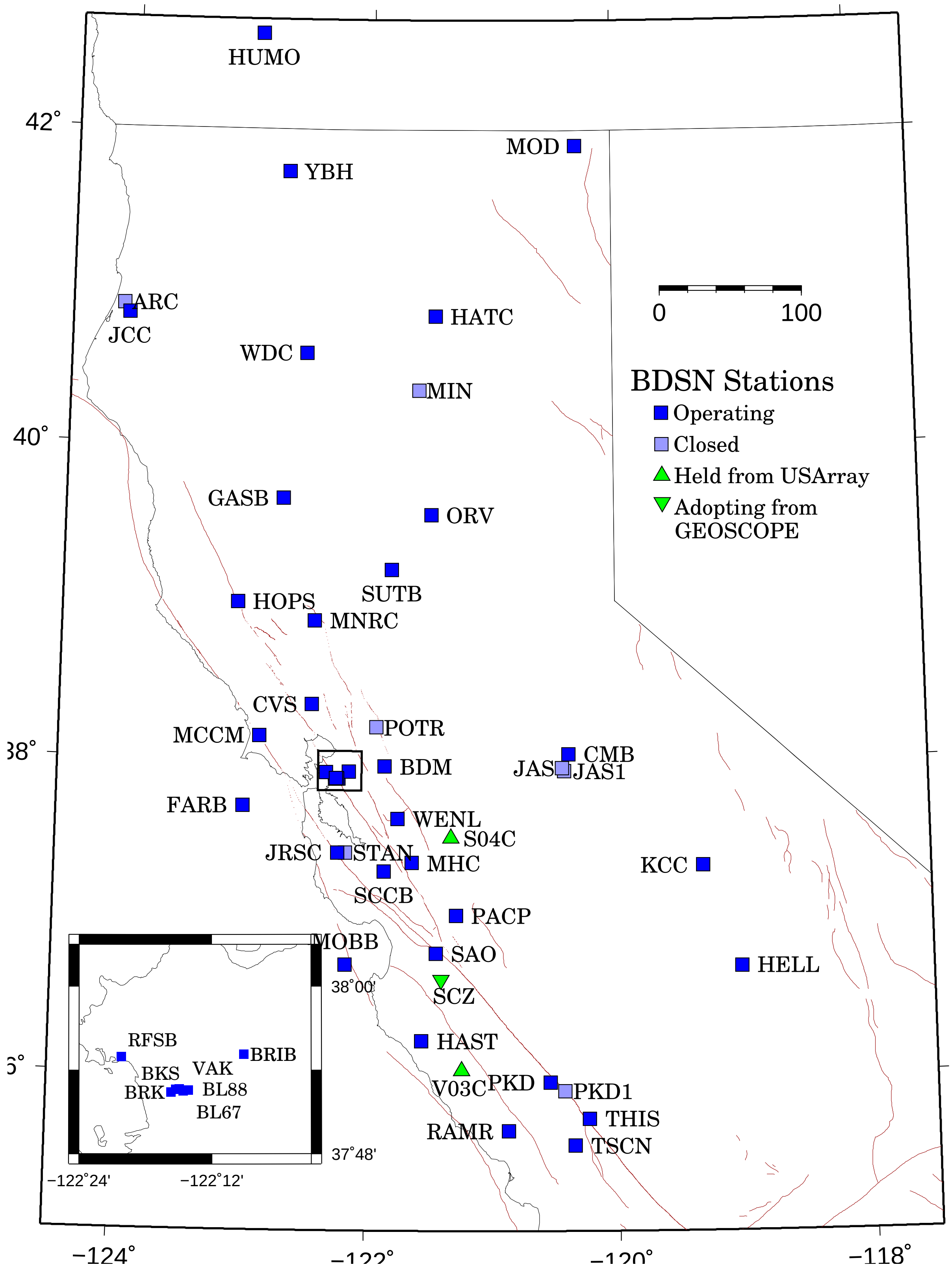

Figure 3.2: Map illustrating the distribution of BDSN stations in Northern and Central California. In the inset map, the order of the stations from left to right is: RFSB, BRK, BL88, VAK, BL67, BKS, BRIB.

1 Berkeley Digital Seismic Network

1.1 Introduction

The Berkeley Digital Seismic Network (BDSN) is a regional network of very broadband and strong motion seismic stations spanning Northern California and linked to UC Berkeley through continuous telemetry (Figure 3.2 and Table 3.1). 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 37 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. This year, field and operation efforts have been directed toward the completion of station upgrades, funded by the American Recovery and Reinvestment Act (ARRA), and the installation of stations for the TremorScope project (see Research Section 3). Engineering and research efforts were also devoted to several projects to develop and test new instrumentation (see Operational Section 7). We have been testing the Quanterra environmental add-on, the QEP. In addition, the BSL is part of a team that is developing and testing a newly designed very broadband (VBB) sensor to replace the STS-1 seismometer.

The expansion of our network to increase the density of state-of-the-art strong motion/broadband seismic stations and 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. In the past (2010-2011), in cooperation with and with support from the Lawrence Berkeley National Laboratory (LBNL), we installed and are collecting data from three sites on the LBNL Campus (VAK, BL88 and BL67). We have been working to develop a site for LBNL equipment in the Lawson Adit on the UCB campus, very close to the fault. This effort is close to bearing fruit. We also received funds from the Gordon and Betty Moore Foundation for TremorScope (see Section 3). As part of this exciting project for monitoring non-volcanic tremor sources along the San Andreas Fault south of Parkfield, the BDSN will be augmented by a network of four high-quality borehole stations and four surface stations. The first two surface stations were installed in the Spring and are collecting data.

Data quality and the integrity of the established network are just as important as network growth, so existing network stations must be preserved. The first generation of broadband seismometers installed by the BSL has been operating for almost 25 years. With funding and equipment from the ARRA, we were able to replace old data loggers at 25 stations. The upgrade of the last remaining BDSN station to have an old Quanterra data logger was completed in June 2011. We continue to exercise vigilance and to commit time and resources to repairs and upgrades as necessary.

1.2 BDSN Overview

Thirty three of the 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 additional 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). Data from all BDSN stations are transmitted to UC Berkeley using continuous telemetry. Continuous telemetry from MOBB was implemented early in 2009. Unfortunately, the underwater cable was trawled and damaged several times, until it failed in late February 2010. The cable was finally replaced in June 2011. In order to avoid data loss during utility disruptions, each site has batteries to supply power for three days; many are accessible via a dialup phone line. The combination of high-dynamic range sensors and digital data loggers ensures that the BDSN has the capability to record the full range of earthquake motion required for source and structure studies. Table 3.2 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 Guralp CMG-3T broadband sensor contributed by LLNL is deployed in a post-hole installation at BRIB. The new TremorScope sites also have Guralp CMT-3T broadband seismometers. A Guralp CMG-1T is deployed at MOBB. All stations, except the TremorScope sites, have either Kinemetrics FBA-ES-T or Metrozet TSA-1 accelerometers with ± 2 g dynamic range. At TremorScope accelerometers are Guralp CMG-5T units, also with ± 2 g dynamic range. Since the end of June 2011, there are no longer any Q680, Q730, or Q4120 Quanterra data loggers in the BDSN. 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

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
BDM	BK	37.9540	-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	-122.2610	49.4	2.7	1994/03 -	Haviland Hall, Berkeley
CMB	BK	38.0346	-120.3865	697.0	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	542.0	3	2006/02 -	Carmel Valley
HATC	BK	40.8161	-121.4612	1009.3	3	2005/05 -	Hat Creek
HELL	BK	36.6801	-119.0228	1140.0	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	-122.1660	-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	37.0080	-121.2870	844	0	2003/06 -	Pacheco Peak
PKD	BK	35.9452	-120.5416	583.0	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	36.7640	-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
SUTB	BK	39.2291	-121.7861	252.0	3	2005/10 -	Sutter Buttes
THIS	BK	35.7140	-120.2370	623.0	0	2012/05 -	South End of Cholame Valley, Shandon
TSCN	BK	35.5440	-121.3481	476.47	0	2012/03 -	Shell Creek North, Shandon
VAK	BK	37.8775	-122.2489	266.0	10	2010/08 -	LBNL Building 46, Berkeley
WDC	BK	40.5799	-122.5411	268.3	75	1992/07 -	Whiskeytown
WENL	BK	37.6221	-121.7570	138.9	30.3	1997/06 -	Wente Vineyards, Livermore
YBH	BK	41.7320	-122.7104	1059.7	60.4	1993/07 -	Yreka Blue Horn Mine, Yreka

Table 3.1: 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-up
BDM	STS-2	FBA-ES-T	Q330HR			FR	
BKS	STS-1	FBA-ES-T	Q330HR		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	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	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			Mi-LAN	X
KCC	STS-1	FBA-ES-T	Q330HR		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	Baseplates, EM	FR	X
SCCB		TSA-100S	Q330HR	X		FR	
SUTB	STS-2	FBA-ES-T	Q330HR	X		R-FR	
THIS	CMG-3T	CMG-5TC	DM24	X		R-Mi	
TSCN	CMG-3T	CMG-5TC	DM24	X		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	FR	X

Table 3.2: Instrumentation of the BDSN as of 06/30/2012. Except for BL88, RFSB, SCCB, and MOBB, each BDSN station consists of collocated broadband and strong-motion sensors, with a 24-bit or 26-bit data logger and GPS timing. The stations BL88, RFSB, and SCCB are strong-motion only, while MOBB has only 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 a ocean current meter (OCM) and differential pressure gauge (DPG). The main and alternate telemetry paths are summarized for each station. 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 2011-2012, 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.

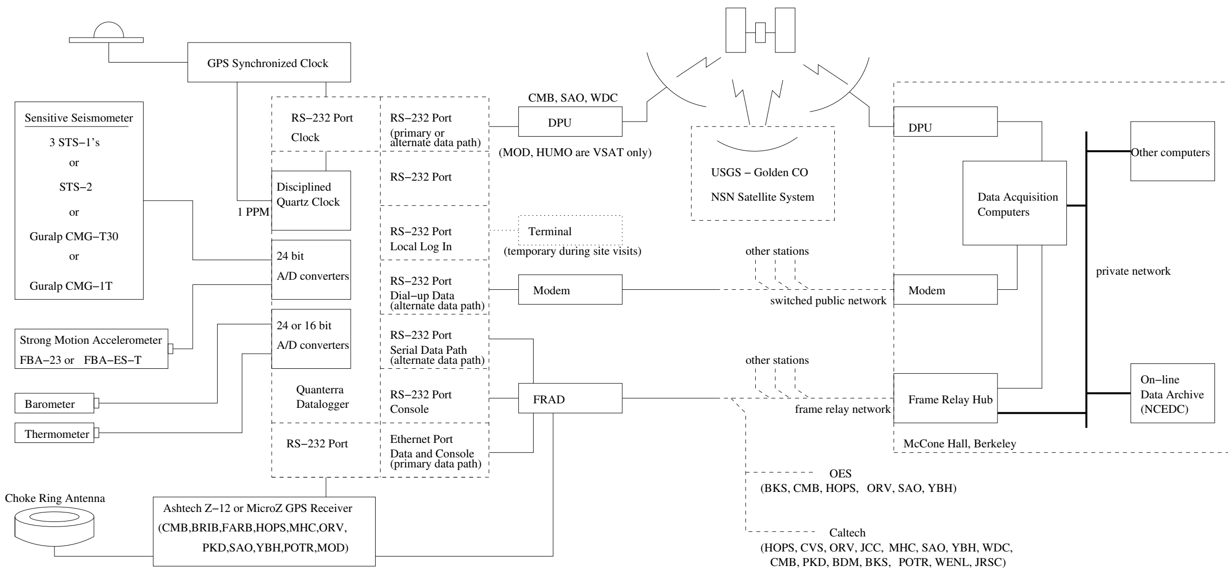

Figure 3.3: Schematic diagram showing the flow of data from the sensors through the data loggers to the central acquisition facilities of the BSL.

Guralp 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?". In addition, the BDSN stations now record continuous data at 0.1, 1.0, 40, and 100 samples per second (Table 3.3). 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, 22 of the BDSN sites use frame-relay telemetry for all or part of their communications system. Other stations send their data to the data center via satellite, Internet, microwave, and/or radio (see Table 3.2).

As described in Operational Section 7, 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 2 and 8). As part of routine quality control (Operational Section 7), 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 3.4 displays BDSN waveforms for the M_w 8.6 earthquake that occurred West of Sumatra on April 11, 2012.

BDSN data are archived and available at the Northern California Earthquake Data Center. This is described in detail in Operational Section 6.

Sensor	Channel	Rate (sps)	Mode	FIR
BB	VH?	0.1	C	Ac
BB	LH?	1	C	Ac
BB	BH?	40	C	Ac
BB	HH?	80/100	C	Ca
SM	LN?	1	C	Ac
SM	BN?	20/40	C	Ac
SM	HN?	80/100	C	Ca&Ac

Table 3.3: 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 LN and BN strong-motion channels are not transmitted over the continuous telemetry but are available on the Quanterra disk system if needed. The HH and HN channels are now all recorded and telemetered continuously at 100 sps and most have causal filtering. In the past, SM channels have been named HL? (BL?, LL?). For past sampling rates, see earlier annual reports.

Electromagnetic Observatories

In 1995, in collaboration with Dr. Frank Morrison, the BSL installed two well-characterized electric and mag-

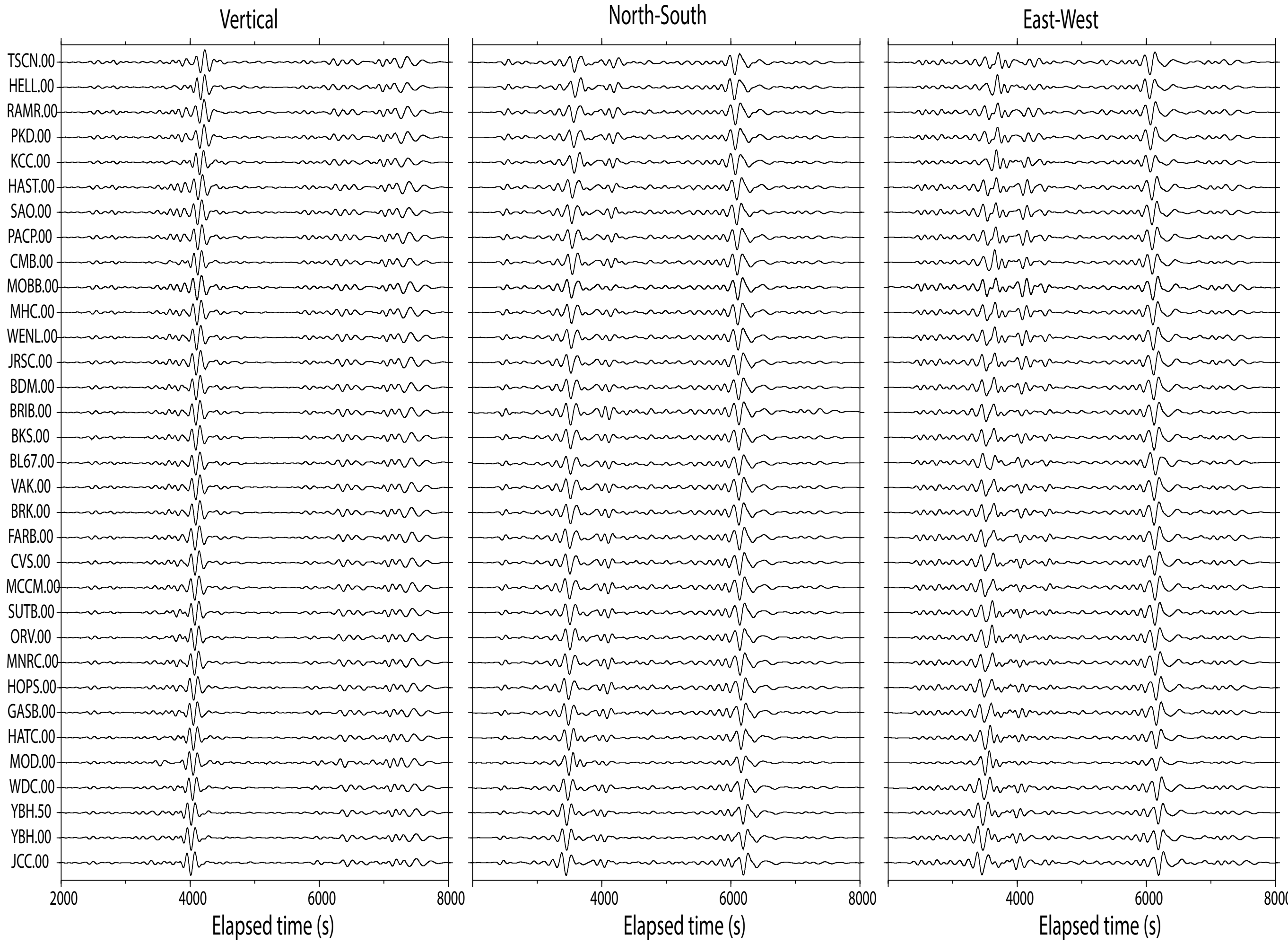

Figure 3.4: Long period (100-333 s period) waveforms recorded across BDSN from the M_w 8.6 teleseism which occurred on April 11, 2012, off the west coast of northern Sumatra at 2.311 N, 93.063 E. The traces are deconvolved to ground velocity, scaled by their maximum values, and ordered from bottom to 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.

netic field measuring systems at two sites along the San Andreas Fault which are part of the Berkeley Digital Seismic Network. Since then, magnetotelluric (MT) data have been continuously recorded at 40 Hz and 1 Hz and archived at the NCEDC (Table 3.4). At least one set of orthogonal electric dipoles measures the vector horizontal electric field, E, and three orthogonal magnetic sensors measure the vector magnetic field, B. These reference sites, now referred to as electromagnetic (EM) observatories, are collocated with seismometer sites so that the field data share the same time base, data acquisition, telemetry, and archiving system as the seismometer outputs.

The MT observatories are located at Parkfield (PKD1, PKD), 300 km south of the San Francisco Bay Area,

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 3.4: 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.

and Hollister (SAO), halfway between San Francisco and Parkfield (Figure 3.2). In 1995, initial sites were established at PKD1 and SAO, separated by a distance of 150 km, and equipped with three induction coils and two 100 m electric dipoles. PKD1 was established as a temporary seismic site, and when a permanent site (PKD) was found, a third MT observatory was installed in 1999 with three induction coils, two 100 m electric dipoles, and two 200 m electric dipoles. PKD and PKD1 ran in parallel for one month in 1999, and then the MT observatory at PKD1 was closed. Starting in 2004, new electromagnetic instrumentation was installed at various Bay Area sites in cooperation with Simon Klemperer at Stanford University. Sensors are installed at JRSC (2004), MHDL (2006) and BRIB (2006/2007).

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

In October 2009, the EM coils at SAO were found to be not working. They were removed and returned to the manufacturer (EMI Schlumberger). They have not yet been reinstalled at SAO. EM/MT equipment at PKD was evaluated in August of 2008. There, the data logger was removed from the PKD EM/MT system and has not yet been returned.

Since it began in 1995, the EM/MT effort has suffered from minimal funding.

1.3 2011-2012 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, 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 benefitted from those funds. We received the new model of Quanterra data logger, the Q330HR, as government-furnished equipment (GFE). Over the course of the next 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 have been replaced with Kinemetrics' newer, lower noise model, the FBA-ES-T.

In addition to the equipment upgrades, we used support from the ARRA project to implement alternative, and less expensive, telemetry options at two stations, at JRSC, on Stanford University's Jasper Ridge Biological Preserve, and at MNRC, on UC Davis's McLaughlin Reserve.

Finally, 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 6 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). To ensure high quality pressure measurements for reducing long period noise in the very broadband recordings, we purchased and will also install the SETRA pressure sensors. During the Spring 2012, we installed all QEP packages and SETRA pressure sensors in a huddle test on the roof of McCone Hall. We have been analyzing the data from that test to corroborate calibration information and evaluate their performance.

In addition, over the past two years, we have been able to purchase and install new electronics, the E300 from Metrozet, for five of our STS-1 sites, KCC, HOPS, BKS, CMB and YBH. Funds for this equipment have come from our IRIS/GSN grant and from our funding from the California Emergency Management Agency (CalEMA).

As always, some of the BSL's technical efforts were directed toward maintaining and repairing existing instrumentation, stations, and infrastructure. While expanding the network continues to be a long term goal of BSL, it is equally important to assure the integrity of the established network and preserve data quality.

New Stations

Two new stations were installed as part of the TremorScope project in the past year, TSCN and THIS. These two stations are surface stations, installed vaults made from plastic septic tanks. To provide thermal mass and reduce noise, the tanks are surrounded by several cubic yards of concrete. Data flow from the stations by radio to USGS microwave hubs at Black Mt. and Hog Canyon. We have been evaluating data from each of these sites, to assess station design and develop improvements for the remaining two surface stations to be installed. We have permitted three of the four borehole locations and have begun to develop plans for the boreholes.

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

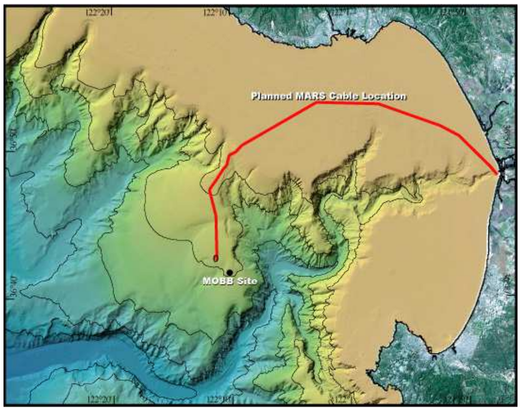

Figure 3.5: Location of the MOBB station in Monterey Bay, California, against seafloor and land topography. The path of the MARS cable is indicated by the solid line.

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).

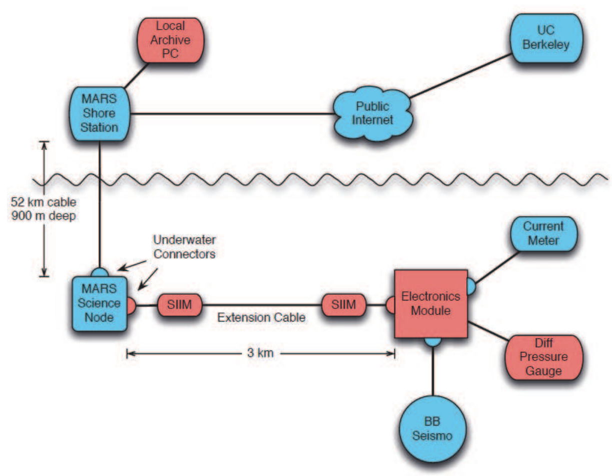

Figure 3.6: Components of the cabled observatory: the MOBB system integrated into the MARS network. MARS-provided components are shown in blue, and components installed or modified by the MOBB team are shown in pink.

The MARS (Monterey Accelerated Research System) observatory (Figure 3.5, `http://www.mbari.org/mars/`) comprises a 52 km electro-optical cable that extends from a shore facility in Moss Landing out to a seafloor node in Monterey Bay (Figure 3.5). The cable was deployed in the spring of 2007, and node installation was completed in November 2008. It now can provide power and data to as many as eight science experiments through underwater electrical connectors. MOBB, located ~3 km from the node, is one of the first instruments to be connected to the cable. The connection was established on February 28, 2009, through an extension cable installed by the ROV Ventana, with the help of a cable-laying toolsled. The data interface at the MARS node is 10/100 Mbit/s Ethernet, which can directly support cables of no more than 100 m in length. To send data over the required 3 km distance, the signals pass through a Science Instrument Interface Module (SIIM) at each end of the extension cable (Figure 3.6). The SIIMs convert the MARS Ethernet signals to Digital Subscriber Line (DSL) signals, which are converted back to Ethernet signals close to the MOBB system. Power from the MARS node is sent over the extension cable at 375 VDC, and then converted to 28 VDC in the distal SIIM for use by the MOBB system. The connection to the MARS node eliminates the need for periodic exchange of the battery and data package using ROV and ship. At the same time, it allows us to acquire seismic data from the seafloor in real time (*Romanowicz* et al., 2009).

The electronics module in the MOBB system was refurbished to support the connection to the MARS observatory. The low-power autonomous data logger was replaced with a PC/104 computer stack running embedded Linux. This new computer runs an Object Ring Buffer (ORB), whose function is to collect data from the various MOBB sensors and forward it to another ORB running on a computer at the MARS shore station. There, the data are archived and then forwarded to a third ORB running at the UC Berkeley Seismological Laboratory. The Linux system acquires data from the various systems on the sea floor: from the Guralp digitizer included in the seismometer package (via RS232) and from a Q330 Quanterra 24 bit A/D converter which digitizes data from the DPG (via Ethernet). It also polls and receives data (via RS232) from the current meter. The data are available through the NCEDC. MOBB data are currently not included in routine earthquake processing as the sampling rate, 20 sps, is relatively low for picking. During the past year, we have implemented a procedure to include "cleaned" MOBB data into the moment tensor analysis program as a first step to using it in earthquake monitoring (see below).

After one year of continuous operation, the MOBB real-time telemetry ceased abruptly as a result of repeated trawling of the extension cable, which was not buried, even though the observatory is located in a protected zone. We obtained funds from NSF/OCE to replace the 3.2 km cable in late 2010, and decided to "go the extra mile" to bury the cable to protect it better from such future occurrences. The MBARI team built a custom-made basket for the ROV Ventana to carry and bury the cable out, while laying it out. The cable was laid out on June 22, 2012 from the Western Flyer and plugged into the MARS system. The next day, the team dropped and installed the datalogger package and the MOBB data came back on-line.

Developing a Noise Removal Procedure for MOBB Seismic Data

On seismograms recorded at ocean bottom seismic (OBS) stations, infragravity-induced noise is generally more dominant on the vertical component than on horizontal components (e.g. *Webb*, 1998). In the absence of other noise and signal sources, the vertical displacement and the pressure are nearly perfectly coherent in the period range 20-200 sec as the seafloor deforms under pressure loading. Because the infragravity noise is continually present in a passband critical for the detection and analysis of seismic surface waves, it is important to suppress the infragravity noise in OBS data. The method we use combines the pressure observations with measurements of the transfer function between vertical seismic and pressure recordings to predict the vertical component deformation signal induced by infragravity waves. The predicted noise signal is then removed from the vertical seismic data in either the frequency or the time domain (*Dolenc et al.*, 2007). In the past year, BSL implemented the noise removal procedure developed by *Dolenc et al.* (2007) into the Moment Tensor Review Interface. This allows the suppression of infragravity-induced noise in MOBB OBS seismic data, improving their suitability for determining moment tensors of moderate earthquakes. The transfer function between the vertical seismic and differential pressure gauge (DPG) signals was first calculated from one year of data taken from March 2009 to March 2010. In the data preprocessing for the moment tensor analysis, the transfer function is combined with pressure measurements for a 3-hour period to predict the vertical component deformation signal induced by infragravity waves. The predicted deformation signal is then removed from the recorded vertical component data in the frequency domain. As a result, most of the infragravity-induced noise is removed. An example of the improvement in signal quality is given in Figure3.7. Here, we used the transfer function to remove infragravity-induced noise on the vertical component for the 2009 Mw 4.3 Morgan Hill earthquake, and confirmed that the method successfully recovered seismic phases that were previously hidden in the infragravity-induced noise. The data was then used for moment tensor analysis in the 10-100 sec period range.

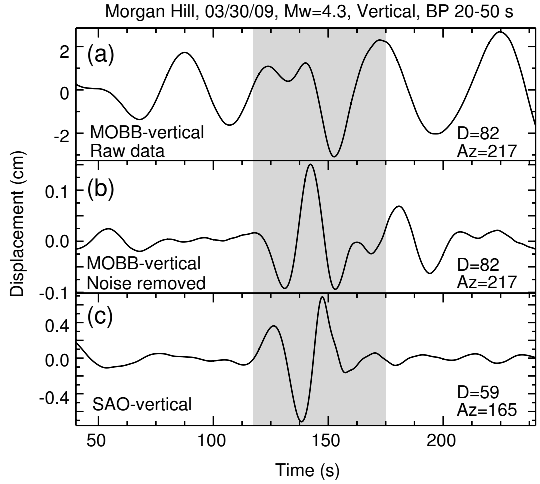

Figure 3.7: Example of the infragravity-induced noise removal procedure for the 2009 Mw 4.3 Morgan Hill earthquake. (a) Original MOBB vertical seismogram and (b) MOBB vertical data after removal of the coherent DPG record by using the transfer function. (c) Station SAO vertical record. A 20-50 sec bandpass filter was applied to all seismic records. Note that the noise-corrected record in (b) shows the earthquake signal (gray area). Also shown are distance (D) in km between earthquake and station and azimuths (Az) in degree from north.

Very Long Period Stations of the BDSN

Great earthquakes excite normal modes in frequency bands around 1 mHz, well below those of smaller earthquakes. The April 11, 2012, M8.6 earthquake which occurred off the west coast of northern Sumatra provided an opportunity to look at the noise levels in these bands at the very broadband BDSN stations, those equipped with STS1s and the very broadband CMG-1T. Figure 3.8 shows spectra in the band from 0.2 mHz to 2 mHz, with clear normal mode peaks for stations YBH, ORV, BKS, CMB and MOBB. SCZ, is a Geoscope station with STS1s in the Central California Coast Ranges. The BSL has been invited to adopt and upgrade this station, which is hosted by UC Santa Cruz. MOBB, the ocean bottom station off of Monterey Bay is just as quiet in this band as other stations such as BKS and CMB. Spectra are not shown for HOPS, KCC, MHC and SAO which are noisy or have glitches. KCC is often noisy because of flowing water. We will review the other stations and resolve the problems causing the noise.

1.4 Acknowledgements

Under Barbara Romanowicz's general supervision, Peggy Hellweg and Doug Neuhauser oversee the BDSN data acquisition operations, and Bill Karavas heads the engineering team. Aaron Enright, John Friday, Joshua Miller, Taka'aki Taira, and Bob Uhrhammer contribute to the operation of the BDSN. The network 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 five of our stations, were purchased with funds from an IRIS/GSN grant and from CalEMA.

MOBB is a collaboration between the BSL and MBARI, involving Barbara Romanowicz, Taka'aki Taira, and Doug Neuhauser from the BSL, and Paul McGill from MBARI. The MBARI team also has included Steve Etchemendy (Director of Marine Operations), Jon Erickson, John Ferreira, Tony Ramirez, and Craig Dawe. 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.

1.5 References

Cox, C., T. Deaton and S. Webb, A deep-sea differential pressure gauge, *J. Atm. Ocean. Tech., 1*, 237-245, 1984.

Crawford W. C., and S. C. Webb, Identifying and removing tilt noise from low-frequency (<0.1 Hz) seafloor vertical seismic data, *Bull. Seis. Soc. Am., 90*, 952-963, 2000.

Dolenc, D., B. Romanowicz, R. Uhrhammer, P. McGill, D. Neuhauser, and D. Stakes, Identifying and removing noise from the Monterey ocean bottom broadband seismic station (MOBB) data, *Geochem. Geophys. Geosyst., 8*, Q02005, doi:10.1029/2006GC001403 (2007).

Murdock, J., and C. Hutt, A new event detector designed for the Seismic Research Observatories, *USGS Open-File-Report 83-0785,* 39 pp., 1983.

Romanowicz, B., D. Stakes, R. Uhrhammer, P. McGill, D. Neuhauser, T. Ramirez, and D. Dolenc, The MOBB experiment: a prototype permanent off-shore ocean bottom broadband station, *EOS Trans. AGU*, Aug 28 issue, 2003.

Romanowicz, B., D. Stakes, D. Dolenc, D. Neuhauser, P. McGill, R. Uhrhammer, and T. Ramirez, The Monterey Bay Broadband Ocean bottom seismic observatory, Ann. Geophys., 49, 607-623, 2006.

Romanowicz, B., P. McGill, D. Neuhauser and D. Dolenc, Acquiring real time data from the broadband ocean bottom seismic observatory at Monterey Bay (MOBB), *Seismol. Res. Lett, 80,* 197-202, 2009.

Webb, S. C., Broad seismology and noise under the ocean, *Rev. Geophys 36*, 105-142, 1998.

Wielandt, E., and J. Steim, A digital very broadband seismograph, *Ann. Geophys., 4*, 227-232, 1986.

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

Zürn, W., and R. Widmer, On noise reduction in vertical seismic records below 2 mHz using local barometric pressure, *Geophys. Res. Lett., 22*, 3537-3540, 1995.

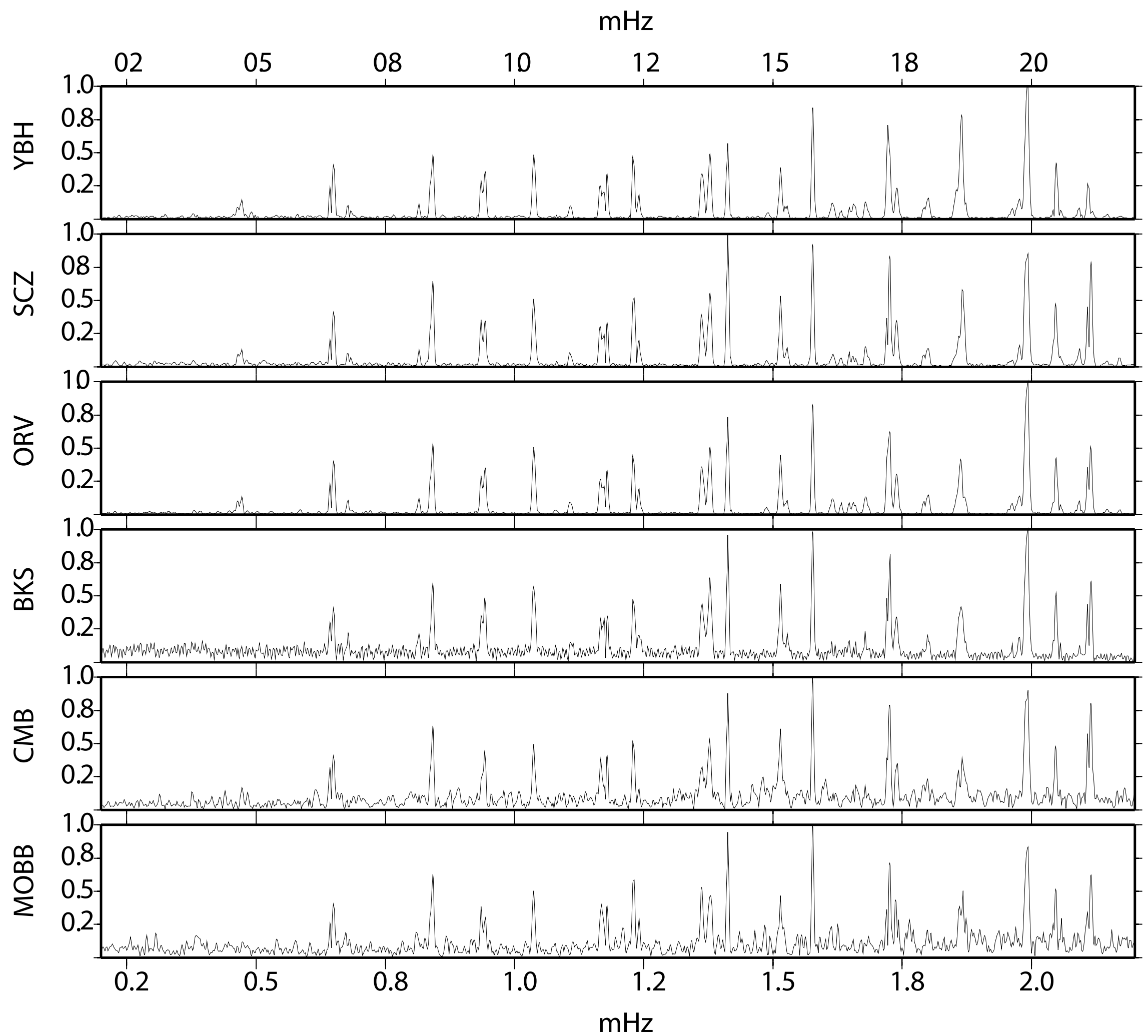

Figure 3.8: Normal mode spectra for the April 11, 2012, M8.6 earthquake which occurred off the west coast of northern Sumatra for the BDSN STS1 stations, MOBB (CMG-1T) and SCZ, a Geoscope station in Central California. Data are converted to acceleration and taken from a 120 hour window starting 0.05 hours after the origin time. A Hann taper has been applied prior to the Fourier transform. The spectra are normalized. Spectra from HOPS, KCC, MHC and SAO are not shown due to noise in their traces. Clearly YBH and ORV have the lowest noise, but the noise in this band at MOBB is similar to other stations such as BKS and CMB.

2 California Integrated Seismic Network

2.1 Introduction

Advances in technology have made it possible to integrate separate earthquake monitoring networks into a single seismic system as well as to unify earthquake monitoring instrumentation. In California, this effort began in the south with the TriNet Project. There, 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 Emergency Management Agency (CalEMA), 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 twelfth year of collaboration and its eleventh year of funding from CalEMA.

2.2 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
- Engineering Strong Motion Data Center: 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 Engineering Strong Motion Data Center 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 CalEMA, oversees CISN projects. The position of chair rotates among the institutions; Ken Hudnut from the USGS Pasadena took over as chair of the Steering Committee in December 2010 from Barbara Romanowicz. Rob Graves will complete the USGS Pasadena term as Steering Committee chair.

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 December 2011. Agendas from the meetings and the resulting reports may be accessed through the CISN website (`http://www.cisn.org/advisory`).

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, San Diego; University of Nevada, Reno; University of Washington; California Department of Water Resources; 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 California. David Oppenheimer of the USGS represents the CISN on the ANSS National Implementation Committee (NIC).

The CISN has recently benefited from the American Recovery and Reinvestment Act (ARRA). The ANSS received funds from the ARRA to improve seismic monitoring throughout the nation and the world. In California, these funds were directed toward replacing old data loggers in both Northern and Southern California, as well as improving installations at individual stations and adding strong motion sites in the form of NetQuakes sensors. The BSL's ARRA-funded activities were mostly completed in previous years, and are described in the corresponding annual reports. The most recently completed ARRA-funded, and other, upgrades are described in are described in Operational Sections 1, 4 and 3.

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.

CISN and CalEMA

CalEMA has long had an interest in coordinated earthquake monitoring. The historical separation between Northern and Southern California and between strong-motion and weak-motion networks resulted in a complicated situation for earthquake response. Thus, CalEMA has been an advocate of increased coordination and collaboration in California earthquake monitoring and encouraged the development of the CISN. In FY 01-02, Governor Gray Davis requested support for the CISN, to be administered through CalEMA. Funding for the California Geological Survey, Caltech and UC Berkeley was made available in spring 2002, officially launching the statewide coordination efforts. Following the first year of funding, CalEMA support led to the establishment of 3-year contracts to UC Berkeley, Caltech, and the California Geological Survey for CISN activities. We have just completed the first year of the fourth three-year contract (2011-2014). Unfortunately, state funding to the CISN has been decreasing as the state's budget problems have increased, putting pressure on our earthquake monitoring and reporting activities.

Past CISN-related activities are described in previous annual reports.

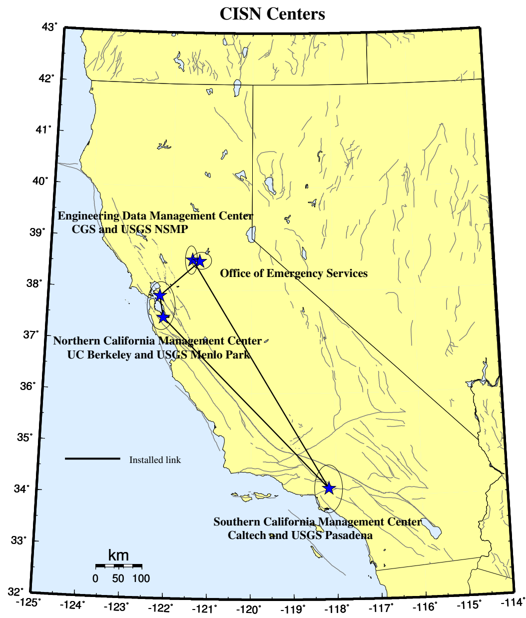

Figure 3.9: Map showing the geographical distribution of the CISN partners and centers. The communications "ring" is shown schematically with installed links (solid lines). It was initially a ring of dedicated T1 connections between the partners. The connections are now less robust, as reduced funding has required that the dedicated service was discontinued. Connections are now available as Internet tunnels.

2.3 2011-2012 Activities

We have just completed the third full year of operation in the NCEMC (Northern California Earthquake Management Center) with the new suite of earthquake monitoring software. In the past, we have called this system 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. As AQMS is being implemented by other regional networks, BSL staff members are providing information and software support to the operators of those networks. The NCEMC made the switch to the AQMS software package in June 2009, and the software is now operating at the BSL and in Menlo Park. CISN funding from CalEMA contributed to this transition, and has supported a number of other activities at the BSL during the past year as well.

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 8 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 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 CalEMA funds, while the second circuit was installed in 2004-2005 (Figure 3.11) 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 one 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 have recently explored prospects of a very high speed radio link between the two data centers.

Statewide Integration

Despite the fact that AQMS software is now operating in both Northern and Southern California, efforts toward

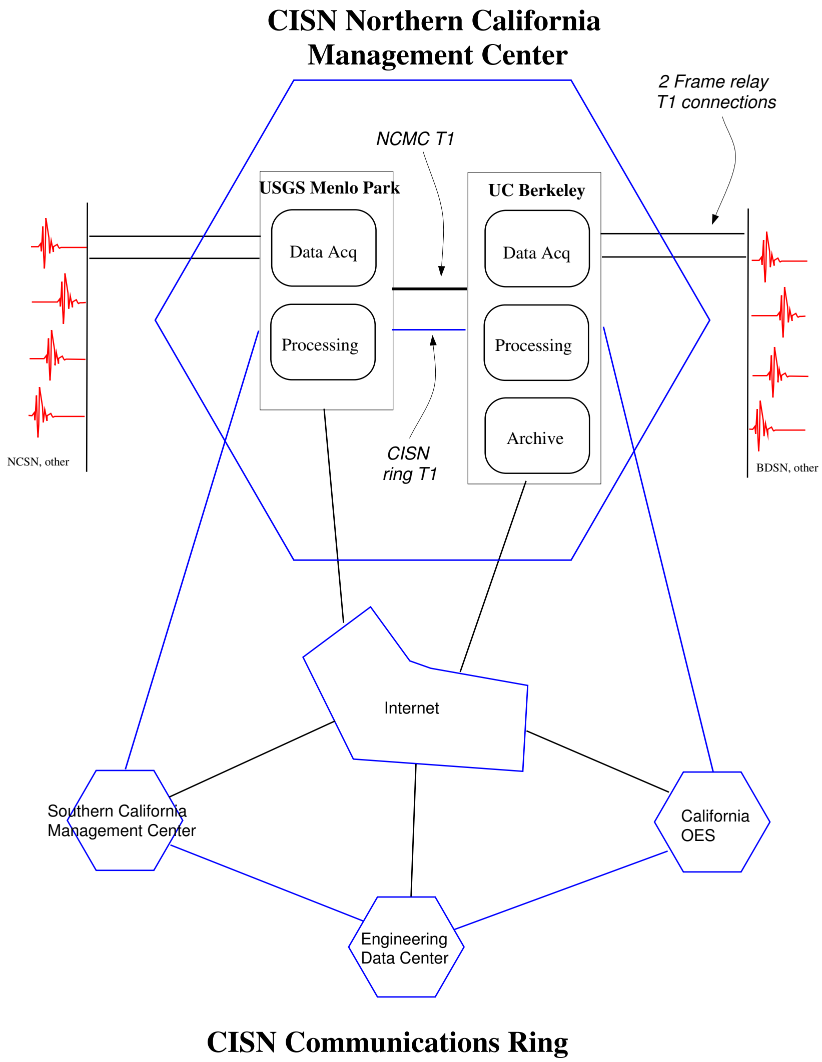

Figure 3.11: Schematic diagram illustrating the connectivity between the real-time processing systems at the USGS Menlo Park and UC Berkeley, forming the Northern California Management Center, and with other elements of the CISN.

statewide integration 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 from meetings and conference calls at `http://www.cisn.org/standards/meetings.html`).

Dual Station Feeds: Early in the existence of CISN, "dual station feeds" were established for 30 stations (15 in Northern California and 15 in Southern California) (Figure 3.10). Because of decreases in funding and other issues, Northern California now sends data from 12 stations to Southern California in real time, and Southern California sends data from 10 to Northern California. The NCEMC uses data from the Southern California stations to estimate magnitudes on a routine basis. In addition, some of 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 at the NCEMC, but not yet statewide. Using a common, and recently improved, format, the CISN partners continue to exchange observations of peak ground motion

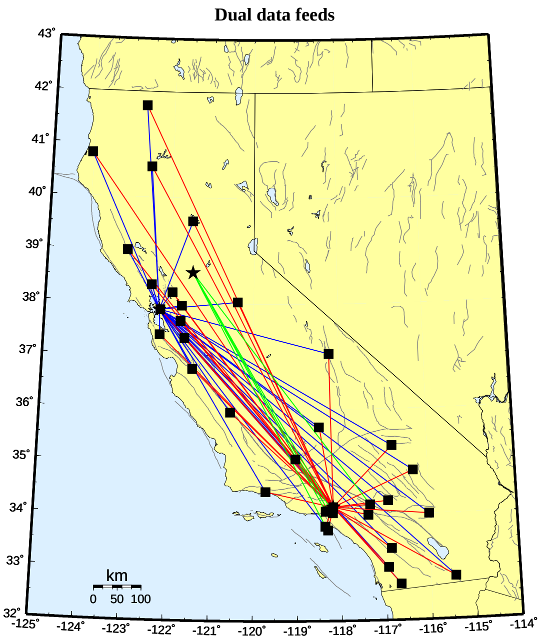

Figure 3.10: Map showing the original 30 stations selected to send data directly to the Northern and Southern California processing centers, and the 5 stations that send data directly to the Engineering Data Center and the Southern California processing center. Due to reductions in funding, now data from only 10 SC stations arrive directly at UCB and data from 12 UCB stations are sent to Caltech.

with one another following an event or a trigger. This step increases the robustness of generating products such as ShakeMap, since all CISN partners now exchange data directly with one another. This also improves the quality of ShakeMaps for events on the boundary between Northern and Southern California, such as the San Simeon earthquake, 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 Strong Motion and Engineering Data Center (SMEDC) in V0 format. We are now working to improve data exchange with the University of Nevada, Reno, for events occurring near the California/Nevada border.

The Software Calibration & Standardization: CISN partners have calibrated and standardized much of the software used for automatic earthquake processing and earthquake review, 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 $logA_o$ function and the associated station-specific corrections for broadband/strong motion stations, and also for strong-motion only stations. We are now focusing magnitude development on adding vertical components, whether short period or broadband, and 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. The Sacramento system uses EIDS (Earthquake Information Distribution System) to collect the authoritative event information for Northern and Southern California. In the CISN, we evaluated the new release of the program, ShakeMap 3.5. In early June, 2011, we finally made the transition to using ShakeMap 3.5 in production. We are evaluating updates to the ShakeMap package before recalculating ShakeMaps for all scenario events, and for all events in the catalog.

A second goal is to improve the robustness of ShakeMap generation and delivery by taking advantage of the fact that ShakeMaps are generated in the Bay Area, Pasadena, and Sacramento.

Moment Tensor Analysis: We have implemented an upgraded version of the complete waveform moment tensor code. This version allows the calculation of full moment tensor solutions, including an isotropic element. In the real time system, only deviatoric solutions will be allowed, but a reviewer may "turn on" the capability to allow full solutions. Using this new package, we are recalculating moment tensors for earthquakes in the Geysers and Long Valley regions, which appeared anomalous using the deviatoric code (see Research Section 15). We have also added code which allows us to use pressure-corrected data from our ocean-bottom station, MOBB (see Operational Section 1). We are working to implement 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.

Location Codes: The CISN adopted a standard for the use of "location" codes (part of the Standard for the Exchange of Earthquake Data [SEED] nomenclature to describe a timeseries based on station-network-channel-location) in the late fall of 2003. USGS and UC Berkeley developers modified the Earthworm software to support their use. After the transition at USGS Menlo Park away from the CUSP analysis system to `Jiggle` in late November 2006, all networks in the CISN implemented location codes in their systems. Now almost all stations in the BK and BP networks operated by the BLS have non-blank location codes. The major effort in this transition was made along with the ARRA-funded upgrades of the data loggers. Surface data loggers digitizing seismic equipment have location code "00." Borehole seismic stations have the location code "40."

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 through it. For example, Menlo Park is responsible for the NSMP, Tremor, and PG&E stations, while Caltech is responsible for the Anza data. 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. This vehicle is expandable, and will probably allow exchange of a more comprehensive set of metadata than dataless SEED volumes, some of which may be necessary for other systems, for example in V0 formatted data.

Standardization: The CISN's focus on standardization of software continues. The complete system is now implemented and providing real-time earthquake information in the NCEMC (see Operational Section 8). The software is currently being implemented at other regional networks of the ANSS.

Earthquake Early Warning: Caltech, the BSL and the ETH Zurich have been using CISN data in real time to test earthquake early warning algorithms and to develop a prototype earthquake early warning system (see sections 21, 20, 22 and 24; see also `http://www.cisn.org/eew`). In 2010-2011, we achieved end-to-end processing, with events being published to a user display. In the past year, we have demonstrated the system to CalEMA, and it is now running at the CalEMA Warning Center in Sacramento. We have also recruited other test users, including BART, Google and other companies and agencies throughout California.

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 responders, organizations with critical lifelines and infrastructure, and emergency responders are invited to register for 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 1.4. Its primary enhancement over the previous version is the development of a kiosk mode for public display purposes.

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 EIDS. The NCEMC uses the EIDS system for publishing earthquake information. In the meantime, the USGS has developed a new tool, the Product Distribution Layer (PDL), initially used for transferring so-called add-on information, such as ShakeMaps. The BSL has been using a PDL system to publish ShakeMaps since June, 2011. We are currently working with USGS in Golden 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.

Outreach

Since FY 05-06, the CISN website (`www.cisn.org`) has been supported by two servers 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 provided access to certain earthquake products directly from `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 `http://www.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 developing 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 `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 state-wide organization of people, institutions and agencies associated with earthquake response and research. In the past year, we publicized the state-wide ShakeOut on October 20, 2011 and participated in it. Due in part to our efforts, the entire UC Berkeley campus participated. We are now working toward the statewide California ShakeOut on October 18, 2012 at 10:18 (see `http://www.shakeout.org` for more information and to sign up).

2.4 Acknowledgements

CISN activities at the BSL are supported by funding from the California Emergency Management Agency, CalEMA.

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, Pete Lombard, Taka'aki Taira, and Stephane Zuzulewski as members.

Because of the breadth of the CISN project, many BSL staff members have been involved, including: Aaron Enright, John Friday, Peggy Hellweg, Ivan Henson, Ingrid Johanson, Bill Karavas, Pete Lombard, Joshua Miller, Doug Neuhauser, Charley Paffenbarger, 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

3.1 Introduction

Complementary to the regional surface broadband and short-period networks, the Hayward Fault Network (HFN) (Figure 3.12 and Table 3.5) is a deployment of borehole-installed, wide-dynamic range seismographic stations along the Hayward Fault and throughout the San Francisco Bay toll bridges system. Development of the HFN 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 increase substantially 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), high-frequency broadband velocity and acceleration data recorded by the NHFN also contributes significantly to 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 non-volcanic 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 $M \sim 0.0$) 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.

3.2 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 are ongoing. 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 in progress, pending completion of the Bay Bridge retrofit. Efforts at acquiring funds for reactivation/upgrade of additional mothballed sites are ongoing.

Fifteen of the remaining 20 stations are currently op-

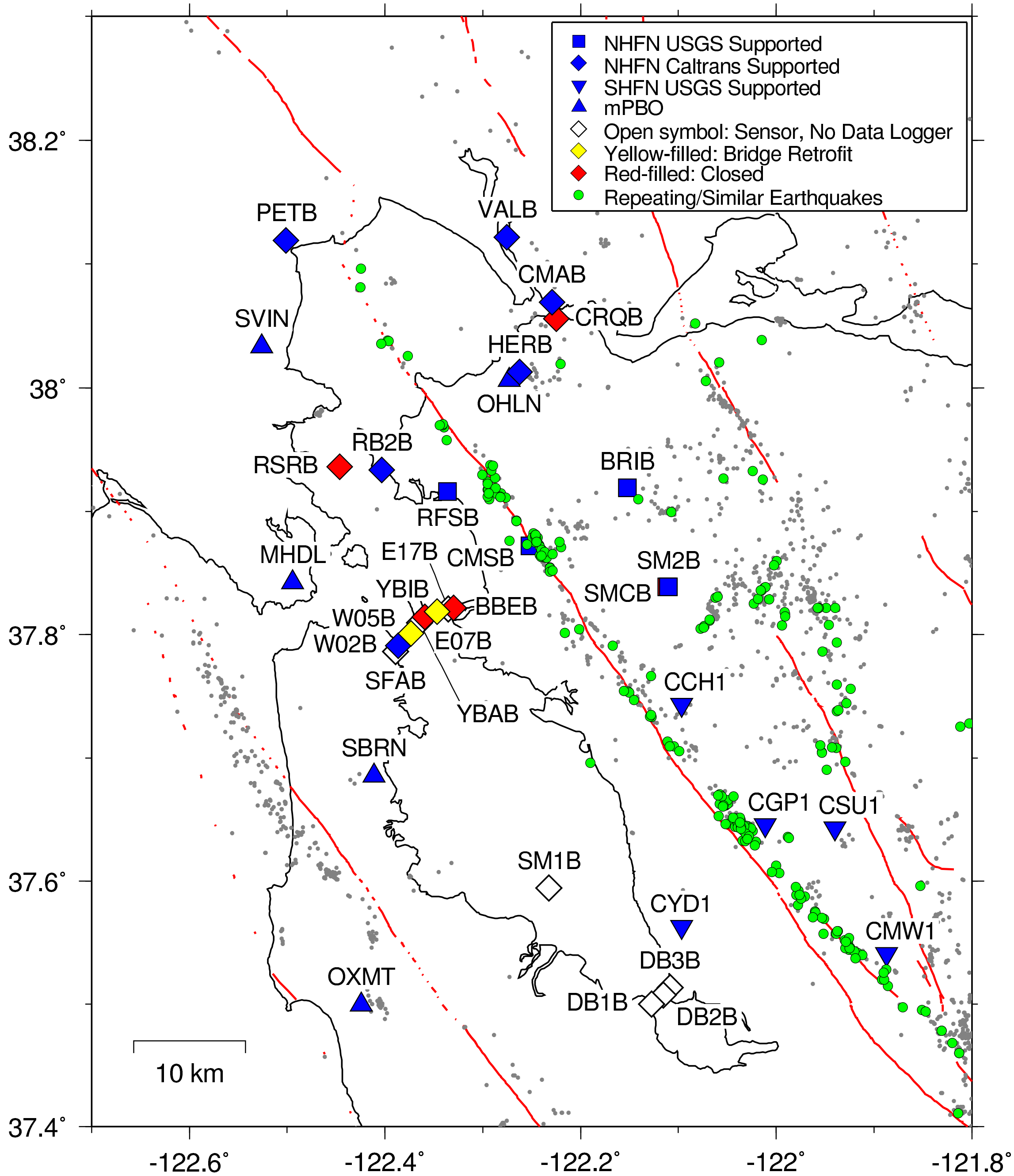

Figure 3.12: Map of HFN and mini-PBO stations. Diamonds are NHFN stations operated by the UC Berkeley Seismological Laboratory (BSL) with previous funding from Caltrans. Squares are BSL NHFN operated sites currently funded by the USGS. Inverted triangles are USGS SHFN sites. Triangles are former mini-PBO stations now part of the NHFN, operated by the BSL and funded by the USGS. Blue (black) are currently operational stations. Red (dark gray) 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). Currently, station BBEB operates only as a telemetry repeater site due to damage from retrofit work. Other sites having downhole sensors but that are currently non-operational are represented as open symbols. 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 relocations (*Waldhauser and Schaff*, 2008) 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.

Sensor	Channel	Rate (sps)	Mode	FIR
Accelerometer	CL?	500.0	T	Ca
Accelerometer	CN?	500.0	T	Ca
Accelerometer	HL?	200.0	C	Ca
Accelerometer	HL?	100.0	C	Ca
Accelerometer	HN?	200.0	C	Ca
Accelerometer	BL?	20.0	C	Ac
Accelerometer	BN?	20.0	C	Ac
Accelerometer	LL?	1.0	C	Ac
Accelerometer	LN?	1.0	C	Ac
Geophone	DP?	500.0	T,C	Ca
Geophone	EP?	200.0	C	Ca
Geophone	EP?	100.0	C	Ca
Geophone	BP?	20.0	C	Ac
Geophone	SP?	20.0	C	Ac
Geophone	LP?	1.0	C	Ac

Table 3.7: 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.

packages are generally installed at depths ranging between 100 and 200 m, the non-backbone, non-operational Dumbarton Bridge sites being exceptions with sensors at multiple depths (Table 3.5).

The five former mPBO sites that are now part of the NHFN have 3-component borehole geophone packages. Velocity measurements for the mPBO sites are provided by Mark Products L-22 2 Hz geophones (Table 3.6). 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 six of the currently operational NHFN backbone sites have Quanterra data loggers, and nine of the operational sites have been upgraded with BASALT data loggers this year. All 15 of these sites telemeter continuously to the BSL, with the exception of CMSB which is temporarily off-line. Signals from these stations are digitized at a variety of data rates up to 500 Hz at 24-bit resolution (Table 3.7). The data loggers employ causal FIR filters at high data rates and acausal FIR filters at lower data rates (see: Table 3.5).

erational (VALB, PETB, CMAB, HERB, BRIB, RFSB, CMSB, SM2B, W02B, RB2B, SVIN, OHLN, MHDL, SBRN, OXMT), though operation of one of the sites (CMSB) has been temporarily suspended pending completion of construction at U.C. Berkeley's Cal Memorial Stadium, and landowner construction at the OHLN site has temporarily disrupted operation at that site. These 15 sites include the five stations folded in from the mPBO project. They telemeter seismic data streams continuously into the BSL's BDSN processing stream with subsequent archival in the Northern California Earthquake Data Center (NCEDC).

The five remaining 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 operate as a telemetry relay site.

Installation/Instrumentation: The NHFN Sensor

Data Rates and Channels: Because of limitations in telemetry bandwidth and local disk storage, 7 of the 10 (excluding CMAB, VALB and PETB) six-component NHFN stations transmit maximum 500 Hz data continuously on only 1 channel of geophone data (i.e., when operational, their vertical geophone channel). Triggered 500 Hz data for 3 additional channels with 180 second snippets are also transmitted. Station VALB also transmits data from only four channels; however, continuous data for all four channels are transmitted 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 10 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-component 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 non-volcanic tremor) at high gain, to high frequencies and with 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.

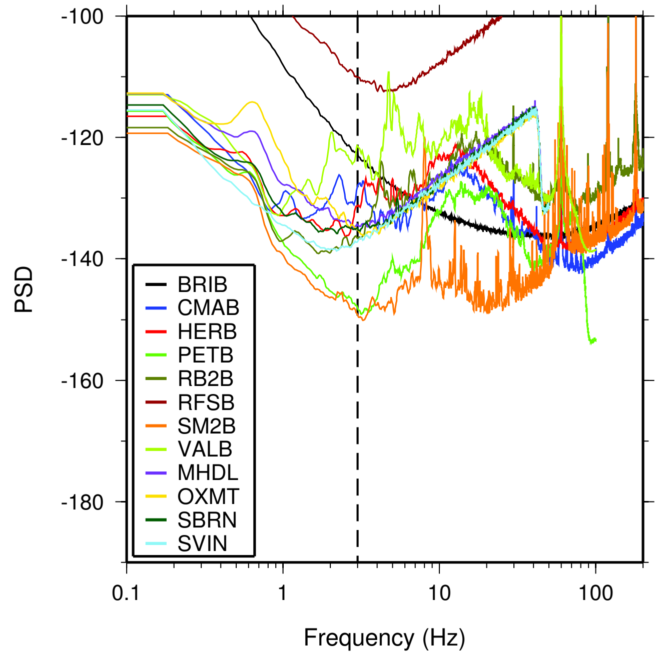

Figure 3.13: Plot showing typically observed background noise PSD for the vertical DP1/EP1 channels of the NHFN borehole stations as a function of frequency. The data are for a 1000 sec period on January 1, 2012 beginning at 01:00 (AM) local time. The PSD ranking (lowest to highest) of the non-mPBO stations (top panel) in operation at the time given at 3 Hz (near minimum PSD for most NHFN stations) is:
SM2B.BK.DP1 -149.943
PETB.BK.EP1 -148.286
RB2B.BK.DP1 -135.750
HERB.BK.DP1 -130.458
CMAB.BK.DP1 -127.173
BRIB.BK.DP1 -122.272
VALB.BK.EP1 -119.649
RFSB.BK.DP1 -108.857
PSD ranking (lowest to highest) for the EP1 channels of the 4 mPBO stations (lower panel) at the time given at 3 Hz)is:
SVIN.BK.EP1 -137.397
OXMT.BK.EP1 -135.051
SBRN.BK.EP1 -134.725
MHDL.BK.EP1 -133.816
Note that there is considerable variation in the general level and structure of the individual station background noise PSD estimates. For example the signals from many of the non-mPBO stations have 60 Hz noise (sometimes accompanied by 120 and 180 Hz harmonics), which is indicative of the presence of ground loops that need to be addressed. If noise spikes at the mPBO stations exist, they are not recorded due to the lower sampling rate of these data. Variations in PSD noise among the stations are also sometimes 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.

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 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 through-put 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)

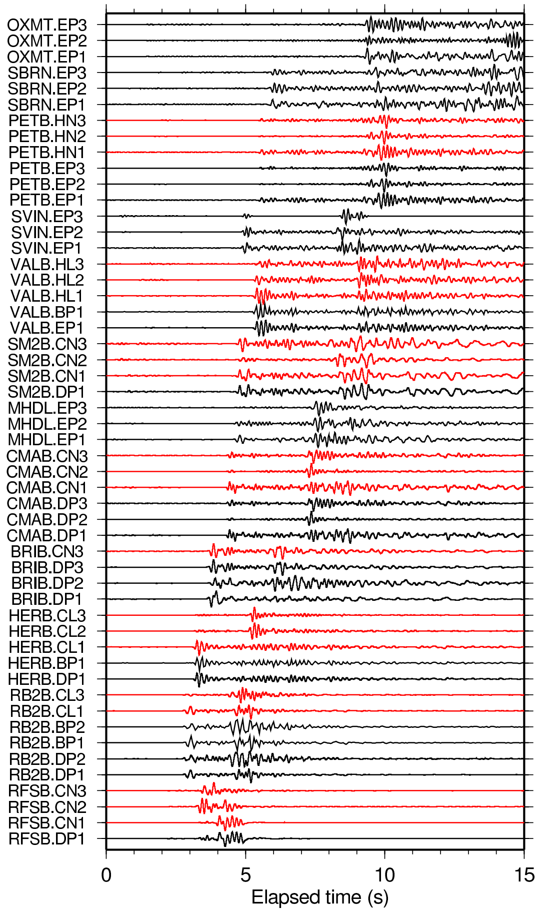

Figure 3.14: Plot of ground accelerations recorded on the geophones (black traces) and accelerometers (red/gray traces) of the 12 NHFN borehole stations in operation at the time of a recent Bay Area earthquake (5 March 2012, M_w 4.0 near El Cerrito, CA). The traces are filtered with a 1-8 Hz bandpass filter, scaled by their maximum values, and ordered from bottom to top by distance from the epicenter.

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.

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. Figure 3.13 shows PSDs of background noise for vertical geophone components of the 12 NHFN stations operating at the time.

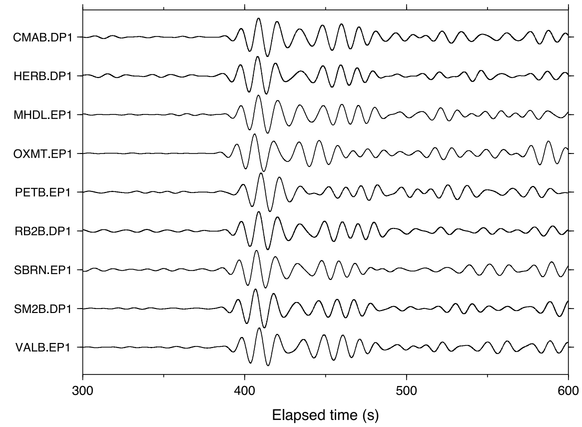

Figure 3.15: Plot of P-wave seismograms of the teleseismic M_w 7.4 earthquake in Oaxaca, Mexico (Lat.: 16.662N; Lon.: 98.188W; depth 20 km) occurring on March 20, 2012 18:02:48 (UTC) recorded on the DP1/EP1 (vertical) channels of the 9 NHFN borehole stations. Data from BRIB, RFSB, and SVIN were not shown because of their lower signal-to-noise ratios. Here, vertical component geophone (velocity) data have been 0.07-0.12 Hz bandpass filtered and normalized by the maximum amplitude for each trace.

By periodically generating such plots, we can rapidly evaluate the network's recording of seismic signals across the wide high-frequency spectrum of the borehole NHFN sensors. 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, SVIN in Figure 3.13) 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, below 60 Hz where power-line noise 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). See, for example the PSD spectrum of stations PETB, RB2B, and SM2B in Figure 3.13). 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 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 is 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 3.14 is an example display of NHFN geophone and accelerometer channels for a recent local Bay Area earthquake (5 March 2012, M_w 4.0 near El Cerrito, CA). It is apparent from this simple display that in general both the velocity and accelerometer channels are operating correctly, though the EP3 channel from station SVIN shows a sensitivity issues that will need to be addresses. Not shown are station W02B recordings that showed no identifiable earthquake signal. The data logger at this station is known to be faulty, and the site is slated for a new BASALT data logger. Stations CMSB and OHLN were off-line at the time, due to landowner construction at those locations.

Figure 3.15 shows seismograms of the recent teleseismic M_w 7.4 earthquake in Oaxaca, Mexico (Lat.: 16.662N; Lon.: 98.188W; depth 20 km) occurring on March 20, 2012 18:02:48 (UTC) On this date and for this frequency band (0.07-0.12 Hz), network performance appears good for the vertical (DP1 and EP1) channels for 9 of the stations in operation at the time.

Owing to their near similar source-receiver paths, 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, after correction for differences in instrument response among the stations. By rapidly generating such plots (particularly with correction for instrument response) 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.

In Figure 3.15, data from BRIB, RFSB, and SVIN were not shown because of the low signal-to-noise ratios on their vertical components for this event. Stations CMSB, OHLN and W02B are also not shown because they did not record the event for reasons cited above. Both Figures 3.14 and 3.15 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 the NHFN.

3.3 2011-2012 Activities

As in every year, routine maintenance, operations, quality control, and data collection play an important part in our activities. In addition, last year, we received funds and government furnished equipment (GFE) data loggers from an American Recovery and Reinvestment Act award through the USGS to update equipment and improve station infrastructure. This year efforts at evaluating and optimizing station performance at the updated sites were carried out.

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) leveraging NHFN activities through partnerships with various institutions outside of BSL

Specific Station issues

BRIB. This year borehole recordings from station BRIB have been showing significant degradation. 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, the problem at the root of the degradation was difficult to identify. After considerable collaborative efforts between analysts and field engineers it was determined that the problem related to the power system at the site. Which aspect of this system is responsible and corrective actions to be taken are still being worked out at this time.

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 has been the case for station OHLN this year, with OHLN being off-line for several months. Landowner construction at the site has now been completed and adaptive modifications of supply of power to OHLN are currently underway. We expect OHLN to be back on-line within a few weeks.

W02B. This site has experienced what appears to be a failure in the data acquisition system. The site is 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, the station has also been neglected. We are now attempting to contact Caltrans to gain access, and plans are to carry out the long overdue general maintenance of the site and to install a new BASALT data logger there.

Additional Funding

Operation of this Bay Area borehole network is funded by the Advanced National Seismic System (ANSS) and 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 support for development and O&M for the remaining stations that have been added to the network through Caltrans partnership grants. Caltrans has also provided additional support for upgrade and expansion when possible.

Due to the state budget crisis, Caltrans has been reviewing and modifying its financial commitments and its accounting practices relating to its funding of external projects, such as the NHFN project. Over the past two years, this has severely complicated efforts to receive previously approved NHFN funding from Caltrans, and has imposed many additional administrative road-blocks 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 over propriety rights has continued. At this time, these roadblocks have brought progress to a standstill, and, though we remain hopeful, formal approval for the proposed project is in doubt.

These delays have put on hold much of our work at maintaining, improving and expanding the Caltrans supported component of the NHFN, so that progress in this area this year has been limited. For the time being, we continue to maintain the previously Caltrans supported stations w/o external support, though at a greatly reduced effort. This is resulting in significantly longer down-time for failed stations and significantly degraded data from several of those stations in need of attention. Eventually, if future support is not forthcoming, these sites will need to be closed.

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, and we have continued to strive for ongoing collaboration with Caltrans. In addition, we and the BSL more generally have 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 NHFN.

3.4 Acknowledgments

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

Under Robert Nadeau's and Doug Dreger's general supervision, Peggy Hellweg, Doug Neuhauser, Taka'aki Taira, and the engineering team (Bill Karavas, John Friday, Aaron Enright, and Joshua Miller) 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). Over the 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.

3.5 References

Rodgers, P.W., A.J. Martin, M.C. Robertson, M.M. Hsu, and D.B. Harris, Signal-Coil Calibration of Electromagnetic Seismometers, *Bull. Seism. Soc. Am., 85(3)*, 845-850, 1995.

Murdock, J. and C. Hutt, A new event detector designed for the Seismic Research Observatories, *USGS Open-File-Report 83-0785,* 39 pages, 1983.

Waldhauser, F. and D.P. Schaff, Large-scale relocation of two decades of Northern California seismicity using cross-correlation and double-difference methods, *J. Geophys. Res., 113*, B08311, doi:10.1029/2007JB005479, 2008.

Code	Net	Latitude	Longitude	Elev (m)	Over (m)	Date	Location
VALB	BK	38.12150	-122.27530	-24.5	155.8	2005/11 - current	Napa River Bridge
PETB	BK	38.11890	-122.50110	-30.0	113.0	2010/09 - current	Petaluma River Bridge
CMAB	BK	38.06892	-122.22914	0.0	142.2	2009/12 - current	Cal Maritime Academy
CRQB	BK	38.05578	-122.22487	-25.0	38.4	1996/07 - 2010/05	CB
HERB	BK	38.01239	-122.26217	-18.0	217.0	2001/09 - current	Hercules
BRIB	BK	37.91886	-122.15179	222.2	108.8	1995/07 - current	BR, Orinda
RFSB	BK	37.91608	-122.33610	-27.3	91.4	1996/02 - current	RFS, Richmond
CMSB	BK	37.87195	-122.25168	94.7	167.6	1995/06 - current	CMS, Berkeley
SMCB	BK	37.83881	-122.11159	180.9	3.4	1998/02 - 2007/06	SMC, Moraga
SM2B	BK	37.83874	-122.11022	200.0	150.9	2007/06 - current	SMC, Moraga
SVIN	BK	38.03318	-122.52632	-27.5	152.4	2003/08 - current	mPBO, St. Vincent's school
OHLN	BK	38.00625	-122.27299	-0.5	196.7	2001/11 - current	mPBO, Ohlone Park
MHDL	BK	37.84232	-122.49431	94.5	151.9	2006/05 - current	mPBO, Marin Headlands
SBRN	BK	37.68561	-122.41127	4.0	161.5	2002/08 - current	mPBO, San Bruno Mtn.
OXMT	BK	37.49936	-122.42431	209.1	194.3	2003/12 - current	mPBO, Ox Mtn.
BBEB	BK	37.82160	-122.32975	-30.8	182.9	2002/09 - 2007/11	BB, Pier E23
E17B	BK	37.82086	-122.33534	TBD	160.0	1995/08 - unknown *	BB, Pier E17
E07B	BK	37.81847	-122.34688	TBD	134.0	1996/02 - unknown +	BB, Pier E7
YBIB	BK	37.81420	-122.35923	-27.0	61.0	1996/07 - 2000/08	BB, Pier E2
YBAB	BK	37.80940	-122.36450	TBD	3.0	1998/06 - unknown *	BB, YB Anchorage
W05B	BK	37.80100	-122.37370	TBD	36.3	1997/10 - unknown +	BB, Pier W5
W02B	BK	37.79112	-122.38632	-45.0	57.6	2003/06 - current	BB, Pier W2
SFAB	BK	37.78610	-122.38930	TBD	0.0	1998/06 - unknown *	BB, SF Anchorage
RSRB	BK	37.93575	-122.44648	-48.0	109.0	1997/06 - 2001/04	RSRB, Pier 34
RB2B	BK	37.93335	-122.40314	-18.0	133.5	2009/12 - current	RSRB, Pier 58
SM1B	BK	37.59403	-122.23242	TBD	298.0	not recorded *	SMB, Pier 343
DB3B	BK	37.51295	-122.10857	TBD	1.5	1994/09 - 1994/11 *	DB, Pier 44
					62.5	1994/09 - 1994/09 *	
					157.9	1994/07 - unknown *	
DB2B	BK	37.50687	-122.11566	TBD		1994/07 - unknown *	DB, Pier 27
					189.2	1992/07 - 1992/11 *	
DB1B	BK	37.49947	-122.12755	TBD	0.0	1994/07 - 1994/09 *	DB, Pier 1
					1.5	1994/09 - 1994/09 *	
					71.6	1994/09 - 1994/09 *	
					228.0	1993/08 - unknown *	
CCH1	NC	37.74332	-122.09657	345.0	119.0	1995/06 - current	Chabot
CGP1	NC	37.64545	-122.01128	461.0	121.0	1995/06 - current	Garin Park
CSU1	NC	37.64303	-121.94020	623.0	124.0	1995/11 - current	Sunol
CYD1	NC	37.56289	-122.09670	114.0	137.0	1996/11 - current	Coyote
CMW1	NC	37.54053	-121.88743	498.0	155.0	1995/06 - current	Mill Creek

Table 3.5: Stations of the Hayward Fault Network. Station code, network id, location, period of available data, and site description are included. 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 (now at LBNL). Latitude and longitude (in degrees) are in WGS84 reference frame. Well head elevation (in meters) is relative to the WGS84 reference ellipsoid. Overburden (depth of sensor package below surface) is in meters. Abbreviations: TBD - to be determined; 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 site CMSB has also been suspended temporarily to accommodate construction at Cal Memorial Stadium on the UC Berkeley campus. At OHLN, temporary suspension of data collection also occurred to accommodate landowner construction.

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	Q4120		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 3.6: Instrumentation of the HFN as of 06/30/2011. Every HFN downhole package consists of collocated 3-component geophones and accelerometers, with the exception of mPBO sites which have only 3-component geophones and are also collecting tensor strainmeter data. Six HFN sites (five of the SHFN and one of the NHFN) 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, 14 are currently telemetering continuous data to the BSL for archiving at the NCEDC, and 1 site (CMSB) is temporarily shutdown due to construction at the Cal Memorial stadium on the U.C. Berkeley Campus. 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 (vertical (Z): -90 $\Rightarrow$ positive counts up; horizontals (H1 and H2): azimuthal direction of positive counts in degrees clockwise from north) are given when known or labeled as TBD if they are yet to be determined. VPN is Virtual Private Network.

4 Parkfield Borehole Network (HRSN)

4.1 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 3.16 shows the location of the network, its 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 a joint station-pair double-difference tomography method (*Zhang et al.,* 2012), and the epicenters of the 1966 and 2004 M6 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 3.8], 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 and 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 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 HRSNs 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 both within the seismogenic (upper ~15 km) and sub-seismogenic depths (~15-35 km), where recently discovered nonvolcanic tremors are occurring (*Nadeau and Dolenc*, 2005).

Parkfield has also become the focus of a major component of NSF's EarthScope (`http://www.earthscope.org`) 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.

4.2 HRSN Overview

Installation of the HRSN deep (200-300 m) borehole sensors initiated in late 1986, and recording of triggered 500 sps earthquake data began in 1987. The HRSN sensors are 3-component geophones in a mutually orthogonal gimbaled package. This ensures that the sensor corresponding to channel DP1 is aligned vertically and that the others are aligned horizontally. 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 Berkeley Seismological Laboratory [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 is underway in 2010-2011 that is allowing for local site storage and later retrieval of data during periods of spo-

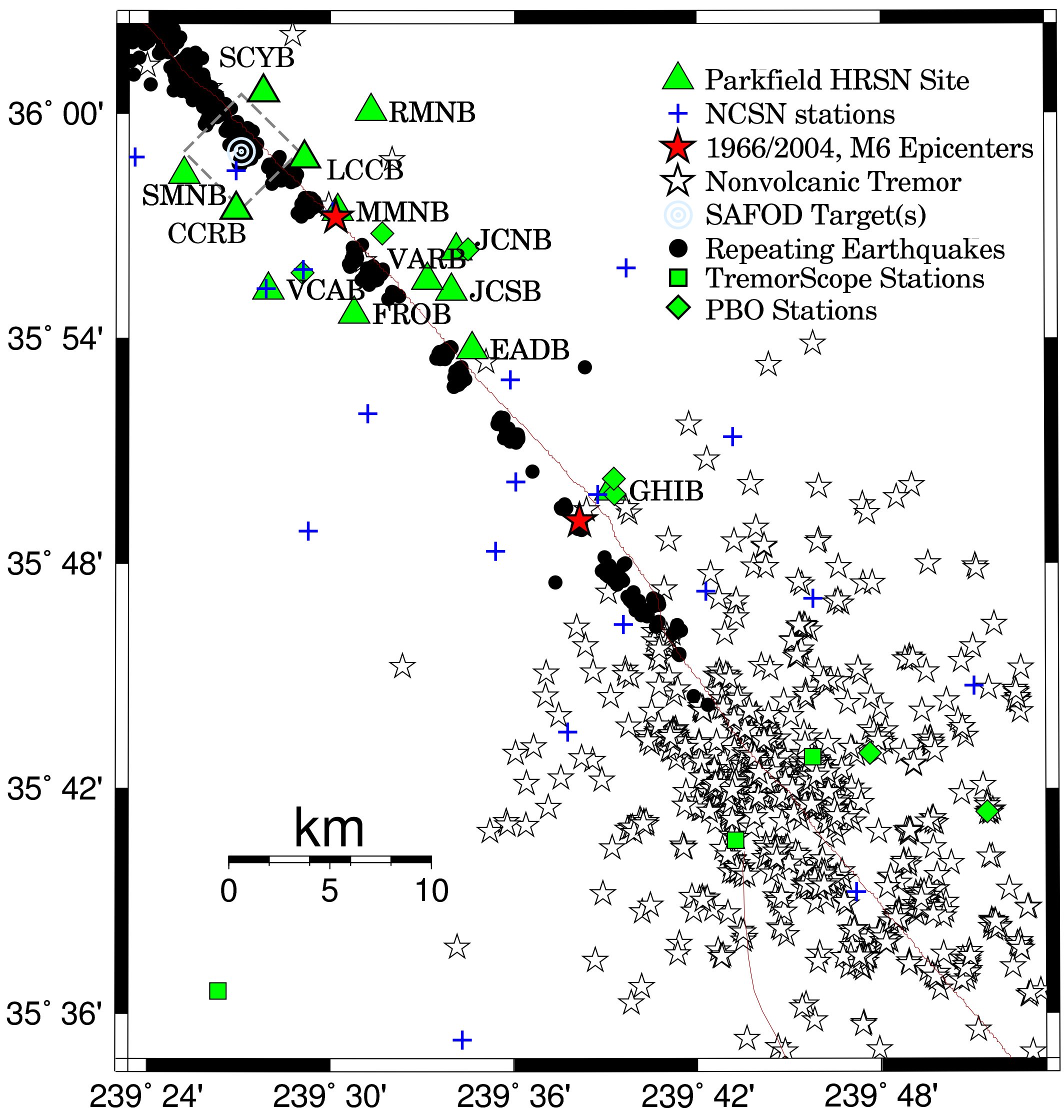

Figure 3.16: Map showing the San Andreas Fault trace and locations of the 13 Parkfield HRSN stations, the repeating M2 SAFOD targets (a 4 km by 4 km dashed box surrounds the SAFOD zone), and the epicenters of the 1966 and 2004 M6 Parkfield mainshocks. Also shown are locations (stars) of nonvolcanic tremors in the Cholame, CA area relocated using a joint hypocenter tomography station-pair double-difference method (*Zhang et al.,* in revision, 2012), and routine locations of clusters of repeating 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. These stations are shown as squares and diamonds, respectively. There are an additional five TremorScope and one PBO station outside the map bounds.

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

Table 3.10: 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.

radic telemetry failures. Properties of the sensors are summarized in Table 3.9.

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 3.16 illustrates the location of the drill site and the new borehole sites, as well as locations of earthquakes recorded by the initial and upgraded/expanded HRSN.

These 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 3.8 and 3.9. All the HRSN data loggers employ FIR filters and extract data at 250 Hz (causal) and 20 Hz (acausal). [Table 3.10].

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 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 through 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 (a replacement repeater path for LCCB was also found this year).

Continuous 20 and 250 Hz data from all HRSN channels are recorded to disk at our central site data collection facility on the California Department of Forestry's (CDF) property in Parkfield. The waveforms are automatically picked at the HRSN computer, and this information is radio telemetered to the USGS site at Carr Hill for 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 for archiving and online access by the community. The HRSN system also generates autonomous event trigger associations which are also archived at the NCEDC.

The HRSN's telemetry system also 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 shut-downs 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 3.17 are surface wave seismograms of the distant region M_w 7.4 earthquake in Oaxaca, Mexico (Lat.: 16.662N; Lon.: 98.188W; depth 20 km) occurring on March 20, 2012 18:02:48 (UTC) and recorded on the SP1 (vertical) channels of the 10 HRSN borehole stations in operation at the time. 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, for the large amplitude surface waves, the vertical channels all appeared to be working well and with proper

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	35.92120	-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	BP	36.00938	-120.53660	945	252	08/2001 -	Stone Canyon

Table 3.8: 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.

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 3.9: 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.

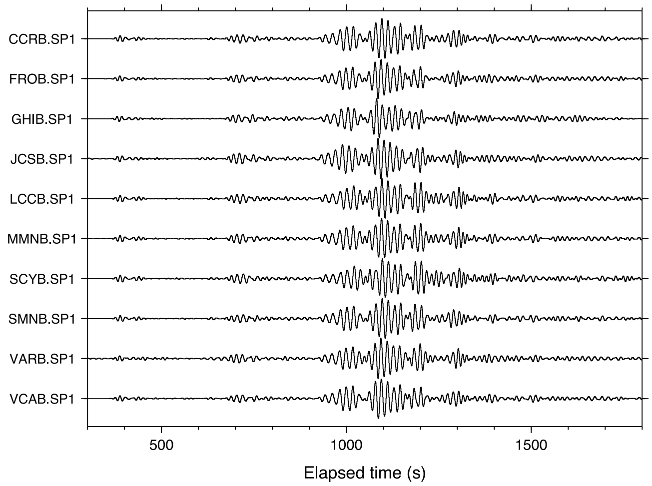

Figure 3.17: Plot of surface wave seismograms of the distant regional M_w 7.4 earthquake in Oaxaca, Mexico (Lat.: 16.662N; Lon.: 98.188W; depth 20 km) occurring on March 20, 2012 at 18:02:48 (UTC) recorded on the SP1 (vertical) channels of the 10 HRSN borehole stations. Data from EADB and JCNB were not shown because of their lower signal-to-noise ratios, and station RMNB no longer records data due to landowner issues. Here, vertical component geophone (velocity) data have been 0.05-0.10 Hz bandpass filtered and normalized by the maximum amplitude for each trace.

polarities. Closer inspection of the unfiltered pre-event noise for these channels and for their corresponding horizontal (DP2 and DP3 channels) indicated that on a finer scale, the following channels were not entirely responding normally to seismic ground motions at the time of this event:

FROB.BP.DP1 - strong 60 Hz noise
LCCB.BP.DP2 - anomalously low signal level
VARB.BP.DP2 - excessive ringing
VARB.BP.DP3 - excessive ringing
EADB.BP.DP1 - no response to earthquake
EADB.BP.DP2 - no response to earthquake
EADB.BP.DP3 - no response to earthquake
JCNB.BP.DP1 - poor signal to noise, post-hole
JCNB.BP.DP2 - poor signal to noise, post-hole
JCNB.BP.DP3 - poor signal to noise, post-hole

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 on the local HRSN computer at the CDF facility. These continuous data are transmitted in near-real-time to the Berkeley Seismological Laboratory (BSL) over a T1 link and then archived at the NCEDC. In addition, the near-real-time data are being transmitted 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. This integration has also significantly increased the sensitivity of the NCSN catalog at lower magnitudes, effectively doubling the number of small earthquake detections in the critical SAFOD zone.

Shortly after being recorded to disk on the central site HRSN computer, event triggers for the individual stations are also 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 that is detected, 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 sensitivity levels. To some degree, this comes at the expense of dynamic range for the larger events (above ~3.5), but high sensitivity is also achieved by recording in the low noise borehole environment (200-300m) and by exhaustive efforts at knocking down extraneous noise sources that arise in the electronics of the recording, power, and telemetry systems or from interference from cultural or scientific noise sources near the stations. As a consequence of the network's high sensitivity, the HRSN also records above its noise floor numerous 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 detections 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, despite the ~50 km distance, the HRSN is detecting San Simeon aftershocks well below magnitude 1.

Current Processing. Since the beginning of the network's data collection in 1987, and up until 2002, the 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 M6 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 had to be 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 realtime 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 microevents from the tens of thousands of San Simeon and Parkfield aftershocks has not been forthcoming, major changes in our approach to cataloging events have had to be implemented. For example, HRSN data flow has now been integrated into NCSN automated event detection, picking, and catalog processing (with no analyst review). 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 -1.0M_L). These new schemes are discussed in more detail in the activities section below.

4.3 2011-2012 Activities

This year, routine operation and maintenance of the HRSN (California's first and longest operating borehole seismic network) have been additionally augmented by funding through the USGS from the American Recovery and Reinvestment Act (ARRA). This funding is directed toward upgrading the data loggers at all sites with government furnished equipment (GFE) data loggers, and with improving and upgrading telemetry and power infrastructure at the sites. Many of the routine maintenance activities described below were also carried out with ARRA support.

In addition to routine operations and maintenance, project activities this year include: a) processing of ongoing similar and repeating very low magnitude seismicity; b) implementing the ARRA upgrades and identifying needed corrections to the upgrades using repeating events; c) supporting SAFOD activities with the repeating and similar event seismicity catalogs; d) monitoring non-volcanic tremor activity in the Parkfield-Cholame area; and e) additional one time adaptations.

Routine Operations and Maintenance

Routine maintenance tasks required this year to keep the HRSN in operation include 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 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 very 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. Shown in Figure 3.18 are power spectral density (PSD) plots of background noise for the 12 vertical HRSN channels in operation at the time (beginning 01:00 AM local time on day 01/01/2012) over a 1000 second period.

By periodically generating such plots, we can rapidly evaluate, through comparison with previously generated plots, 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 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 with the PSD analyses, further remote tests can be made to more specifically determine possible causes for the problem, and corrective measures can then be planned in advance of field deployment within a relatively short period of time.

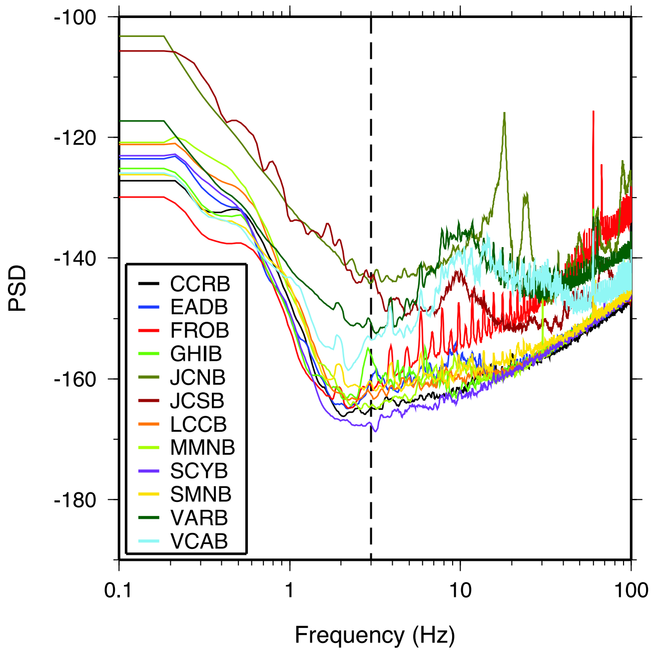

Figure 3.18: Background noise Power Spectral Density (PSD) levels as a function of frequency for the twelve 250 sps vertical component channels (DP1) of the HRSN borehole stations in operation during the 1000 second period analyzed, beginning 01:00 AM local time on day 01/01/2012. The approximate 2 Hz minimum of the PSD levels occurs because of the 2 Hz sensors used at these sites. Below 2 Hz, noise levels rise rapidly. The PSD (dB) ranking (lowest to highest) at 3 Hz (intersection with vertical line) for the vertical channels is:
SCYB.BP.DP1 -167.217
MMNB.BP.DP1 -164.746
CCRB.BP.DP1 -164.630
LCCB.BP.DP1 -163.346
FROB.BP.DP1 -161.281
SMNB.BP.DP1 -160.395
EADB.BP.DP1 -159.894
GHIB.BP.DP1 -157.995
VCAB.BP.DP1 -152.920
VARB.BP.DP1 -150.796
JCNB.BP.DP1 -145.028
JCSB.BP.DP1 -144.259
Note that station RMNB is now closed due to landowner issues and failed station JCNB (failure in late 2007) has been reopened as a post-hole installation.

Similar and Repeating Event Catalogs

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 micro-earthquakes, and the increased interest in using the micro-quakes 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 micro-earthquakes 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 generally have NCSN magnitude determinations associated with them.

These limitations can severely hamper research efforts relying on the more numerous similar and characteristically repeating micro-events (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 micro-events 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 micro-events ranging over about 3 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 characteristically repeating microearthquakes (i.e., near identical earthquakes) occurring within the similar event family (Figure 3.19). The pattern scanning approach also ensures optimal completeness of repeating sequences owing to scans of the matching pattern through "all" available continuous data (critical for applications relying on recurrence interval information). For example, only about half of the magnitude 0.26 events shown in Figure 3.19 were picked up by the NCSN-HRSN integrated network.

Figure 3.19 also shows how stable the performance of the borehole VCAB.BP.DP1 channel has remained over the ∼4.5 year period shown. Due to station malfunctions or human error during field maintenance, this would not necessarily be the case. Because repeating events can generally be 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 1 to 2 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) 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 3.20) 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 worked at adapting our cataloging codes to take advantage of faster computing now available. We have expanded the library of reference event patterns and plan to retroactively scan 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 ARRA upgrade of the HRSN).

Progress on ARRA upgrades

This year, funding through the USGS from the American Recovery and Reinvestment Act (ARRA) was used to complete upgrade of data loggers at all sites with government furnished equipment (GFE) data loggers, and for improving and upgrading telemetry and power infrastructure at the sites. Because of increased use of pattern-match scanning techniques through continuous seismograms to detect and process repeating and Low Frequency Events (LFEs), care is being taken in our upgrade efforts to maintain the response characteristics of the HRSN's continuous data. At the time of this report, all 12 of the open HRSN stations have had new BASALT data loggers installed, with corresponding power and telemetry infrastructure upgrades. A station (JCNB), whose connection to its downhole sensor (cemented in place) was severed, has now had a new sensor emplaced at ∼ 4 m depth and is fully operational.

The repeating and similar event data we are compiling provide nearly ideal natural sources for ensuring the stability of the HRSN station's response characteristics across the transition to ARRA upgrade electronics. In comparing waveforms from repeating events before and after the the first two BASALT installations (i.e., at FROB and MMNB), it became immediately apparent that the nominal polarities of the BASALT data loggers were of the opposite sign to those of their predecessors (Q730s). In subsequent installations, this was taken into account. We were also immediately able to recognize in the repeating event waveforms that the horizontal channel assignments were switched in about half of the cases (i.e., DP2 mapped to DP3 and DP3 mapped to DP2). Whether this was due to incorrect cable preparation or to incorrect documentation is still not known, but subsequent site visits and analyses of ongoing repeat event waveforms are being used to correct and confirm appropriate channel assignments and polarities.

The repeating earthquake analyses have also shown that, absent the polarity flips, channel swaps and superposed signals, preservation of the the waveform and spectral shapes and spectral phasing relative the Q730 predecessors is very good. However, the analyses do reveal a significant (∼15-20%) drop in the amplitude of the BASALT signals relative to the Q730s. At this time it appears this could involve an impedance matching issue at the interface of the BASALT with the other components of the HRSN stations. This is currently being investigated further, and corrective measures are being considered.

Tremor Monitoring

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 research. The Cholame tremors occupy a critical location between the smaller Parkfield (∼M6) and much larger Ft. Tejon (∼M8) rupture zones of the SAF (Figure 3.16). Because the time-varying nature of tremor

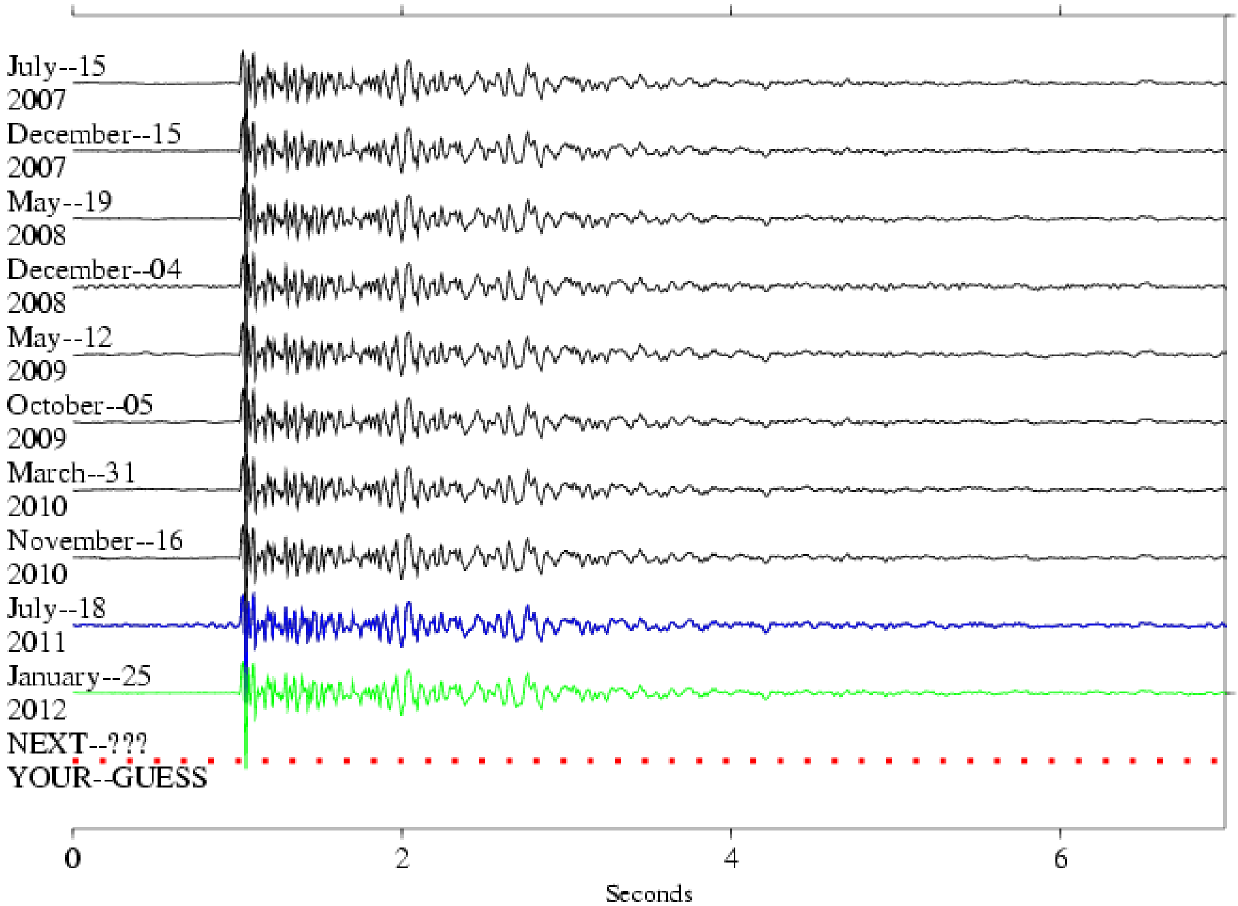

Figure 3.19: Ten most recent repeats of a characteristic sequence of repeating magnitude 0.26 (M_p, USGS preferred magnitude) microearthquakes recorded by vertical (DP1) channel of HRSN station VCAB. Characteristically repeating micro-events are extremely similar in waveform (typically 0.95 cross-correlation or better). High-precision 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).

In last year's annual report we noted that the recurrence intervals for events in this sequence were on the order of 6 to 8 months, and we predicted 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/dark-gray) confirmed our prediction, and a subsequent repeat on January 25, 2012 (green/light-gray) also followed the 6 to 8 month recurrence pattern. 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 anticipate at least one and possibly two additional repeats within the next year, with the next repeat expected to occur sometime in July through September of 2012. 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.

activity is believed to reflect time-varying deep deformation and presumably episodes of accelerated stressing of faults, because anomalous changes in Cholame area NVT activity preceded the 2004 Parkfield M6 earthquake, and because elevated tremor activity has continued since the 2004 Parkfield event, 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 3087 NVT bursts have been identified and cat-

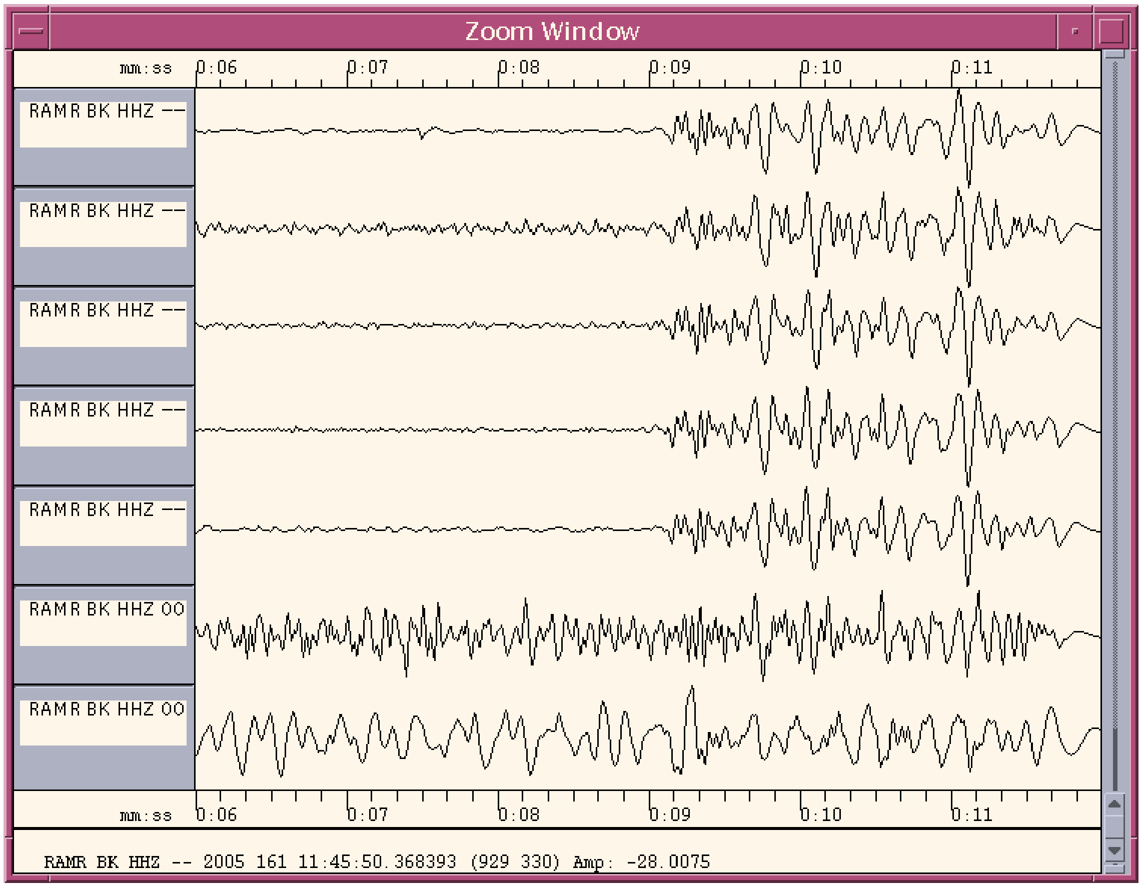

Figure 3.20: Figure of repeating earthquake data illustrating their utility for identifying problematic channel responses. Here a repeat of EarthScope's SAFOD LA sequence (∼M1.7) occurring on 21 March 2012 was identified using HRSN stations. The event was large enough, however, to use the repeating sequence waveforms to evaluate the performance of stations from other networks out to distances greater than 50 km from the HRSN. Shown are the last 7 LA sequence events recorded on the HH vertical channel of Berkeley's Broadband station RAMR (formerly EarthScope TA station V04C) high-pass filtered at 3 Hz. RAMR is 55 km from the repeating events. From top to bottom, the events occurred on 01/23/2005, 06/10/2005, 01/28/2006, 05/30/2007, 12/19/2007, 10/21/2010, and 03/21/2012, respectively. Waveforms for the first 5 events are well recorded and consistent, indicating healthy station response. However, between the 2008 and 2010 events a significant degradation in response for frequencies above 3 Hz is seen to have taken place. Signal from the 2010 event is only just visible above the noise. For the 2012 repeat (bottom waveform), no signal is visible at all in the RAMR waveform. This affects all recorded broadband channels at RAMR. We are currently investigating the problem.

aloged, and regular updates of the NVT catalog continue on a biweekly basis.

Efforts in Support of SAFOD

An intensive and ongoing effort by the EarthScope component called SAFOD (San Andreas Fault Observatory at Depth) is underway to drill through, sample, and monitor the active San Andreas Fault at seismogenic depths and in very close proximity (within a few tens of kilometers or less) to a repeating magnitude 2 earthquake site. The HRSN data plays a key role in these efforts by providing low noise and high sensitivity seismic waveforms from active and passive sources, and by providing a backbone of very small earthquake detections and 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 long-term monitoring of the ongoing chemical, physical, seismological, and deformational properties in the zone (particularly any signals that might be associated with the next repeat of the SAFOD repeating 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 on the Web-based NCEDC. 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) catalog has taken place this year, with particular focus on expansion and refinement of repeating event data within the 1.5 cubic km volume centered on the SAFOD target zone. Last year, 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) over 1200 earthquakes within this small volume. 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 this year to remove redundant events from the over-all 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. This year, we have continued to monitor these sequences and have expanded the catalog of similar and repeating events in the immediate SAFOD zone by over 75 earthquakes. We also identified the only repeat of the 3 main SAFOD sequences. It occurred on 21 March of 2012 and was a member of the LA sequence.

Additional One Time Adaptations

Owing to the break-down of negotiations with the landowner of Gastro Peak this year, we have closed station RMNB. Because RMNB also served as a repeater site for LCCB, we have also had to locate and implement an alternative telemetry path for LCCB through relay site PMM. Tests on the implementation show that despite a less than optimal path, the telemetry seems to be operating properly. Monitoring of the through-put continues to confirm robust year-round telemetry.

Telemetry through-put from the CDF to the USGS link at Carr Hill has degraded over time, and tests have revealed that the continued growth of tree branches within the telemetry path was most likely responsible. It was also recognized that the telemetry scheme between the CDF and Carr Hill was less than optimal and that the through-put problem could be largely compensated for with a streamlined scheme. In the past, CDF waveforms were sent to Carr Hill for phase picking by the NCSS processor at Carr Hill, requiring substantial band-width. In cooperation with our USGS partner, we have now transferred the phase picking task to the CDF computer and instead of sending waveforms, we now send just the picks to Carr Hill for NCSS processing, vastly reducing the bandwidth load on the CDF to Carr Hill telemetry link.

4.4 Acknowledgments

Under Robert Nadeau's and Doug Dreger's general supervision, Peggy Hellweg, Doug Neuhauser, Taka'aki Taira, and the engineering team (Bill Karavas, John Friday, Aaron Enright, and Joshua Miller) 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. Additional improvements in the power and telemetry systems were funded under the USGS ARRA grant G09AC00487.

4.5 References

Bakun, W. H., and A. G. Lindh, The Parkfield, California, prediction experiment, *Earthq. Predict. Res., 3*, 285-304, 1985.

Hickman, S., M.D. Zoback and W. Ellsworth, Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth, *Geophys. Res. Lett., 31*, L12S01, doi:10.1029/2004GL020688, 2004.

Michelini, A. and T.V. McEvilly, Seismological studies at Parkfield: I. Simultaneous inversion for velocity structure and hypocenters using B-splines parameterization, *Bull. Seismol. Soc. Am., 81*, 524-552, 1991.

Nadeau, R.M. and D. Dolenc, Nonvolcanic Tremors Deep Beneath the San Andreas Fault, *SCIENCE, 307*, 389, 2005.

Shelly, D.R., W.L. Ellsworth, T. Ryberg, C. Haberland, G.S. Fuis, J. Murphy, R.M. Nadeau and R. Bürgmann, Precise location of San Andreas Fault Tremors near Cholame, California using seismometer clusters: Slip on the deep extension of the fault?, *Geophys. Res. Lett., 36*, L01303, doi:10.1029/2008GL036367, 2009.

Thurber, C., H. Zhang, F. Waldhauser, J. Hardebeck and A. Michael, Three-dimensional compressional wavespeed model, earthquake relocations, and focal mechanisms for the Parkfield, California region, *Bull. Seismol. Soc. Am., 96*, S38-S49, doi:10.1785/0120050825, 2006.

Zhang, H., R.M. Nadeau, R.N. Toksoz, C.H. Thurber and M. Fehler, Nonvolcanic Tremors in Localized Low Shear Wave Velocity Zones Beneath the San Andreas Fault, *J. Geophys. Res.,* (in revision), 2012.

5 Bay Area Regional Deformation Network

5.1 Background

The Bay Area Regional Deformation (BARD) network is a collection of permanent, continuously operating GPS receivers that monitors crustal deformation in the San Francisco Bay Area 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 (Table 3.11), while additional stations operated by the USGS, US Coast Guard and others fill out the extended BARD network.

Since the completion of 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 3.21). Together, PBO and BARD stations provide valuable information on the spatial complexity of deformation in the San Francisco Bay Area 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 (Table 3.11) and stream their data in real time to the BSL. Data in turn is provided in real time to the public. Furthermore, nineteen BARD Backbone sites are collocated with broadband seismic stations of the Berkeley Digital Seismic Network (BDSN), with which they share continuous telemetry to UC Berkeley (Table 3.11). As geodetic and seismic data become more closely integrated, these collocated stations are already available to provide combined data products.

This past year saw the completion of work performed under the American Reinvestment and Recovery Act (ARRA). Sixteen BARD sites were upgraded with more modern receivers (Topcon Net-3GA) that provide BINEX data streams with 1 Hz sampling over TCP/IP. The new receivers are also capable of recording L5 data in addition to L1 and L2; L5 is a third frequency that will be added to GPS satellites in the coming years. The BSL also received ARRA funding to install seven new stations at existing BDSN stations (Table 3.11), thereby taking advantage of shared telemetry. Six of these stations (GASB, JRSC, MCCM, MNRC, PTRO, and WDCB) have been installed, while winter weather hampered construction of the seventh monument (HELL), which will be completed this summer.

5.2 BARD Overview

BARD station configuration

Following upgrades, the BARD network now includes just two models of receiver: Trimble NetRS and Topcon Net-G3A. The Topcon receivers replaced ones which were connected directly via serial connection and were thus susceptible to data loss during telemetry outages. The upgraded receivers should allow us to provide complete daily data. We were also able to finally upgrade the last two low-rate stations to high data collection rate (LUTZ, SODB), such that the entire BARD network now streams, collects and archives data at 1 Hz. 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. Other methods include a direct radio link to Berkeley (TIBB) and satellite telemetry. At MODB, 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). We also changed our data strategy by allowing some data to be transferred by web-based telemetry (ADSL lines). This will reduce our communication operational costs and, we hope, will not affect our ability to react in the case of a large event.

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 three years, and their stability over long periods

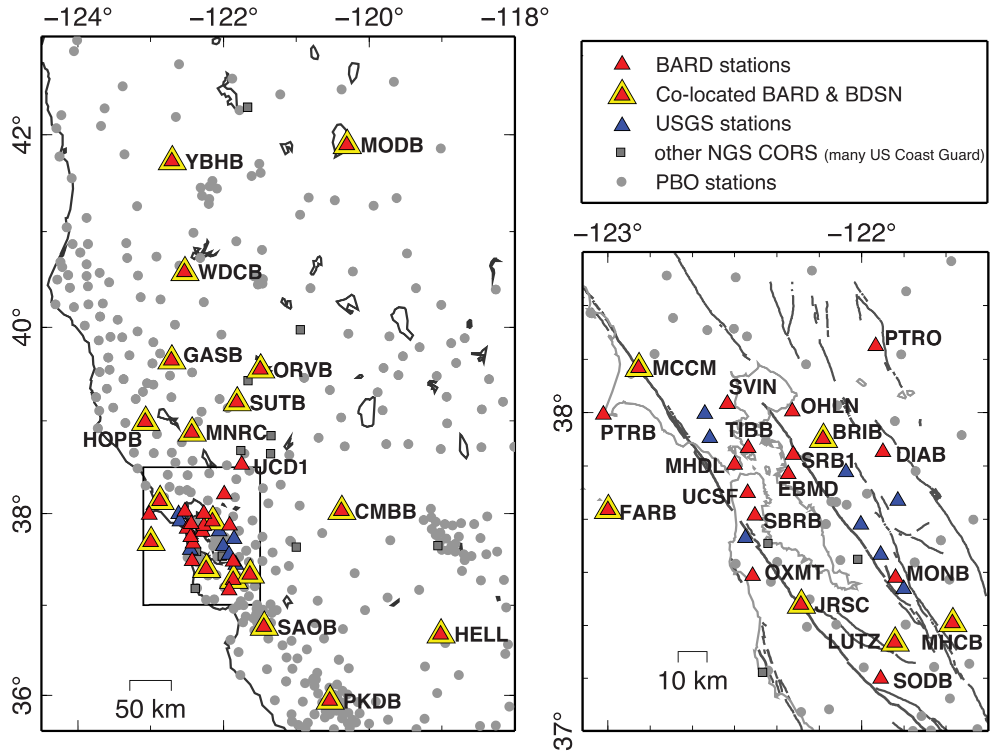

Figure 3.21: Map of the BARD Backbone network and surrounding PBO sites in Northern California. Box in left figure indicates the extent of the figure on right.

of time is yet to be evaluated.

Data archival

Raw and RINEX data files from the 31 BARD Backbone stations and several other stations run by BARD collaborators, such 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 2 hours 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 World Wide Web (`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. The NCEDC continues to archive 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. Quality control efforts were implemented by the NCEDC to ensure that raw data, scanned site log sheets, and RINEX data are archived for each survey. All of the USGS/MP GPS data has been transferred to the NCEDC, and virtually all of the data from 1992 to the present has been archived and is available for distribution. These survey-mode data are used together with data from BARD and PBO stations to produce BAVU (Bay Area 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 currently 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. The streams are available in BINEX and RTCM formats from a Ntrip caster operated by the BSL (`http://earthquakes.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.

Data processing

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 (*King and Bock*, 1999, *Herring*, 2005). 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 or L3). Baseline solutions are loosely constrained until they are combined together. 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*, 2005). 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 (*dAlessio 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. An updated, though preliminary, version of the BAVU velocity model has been completed, which includes BARD stations (BAVU3β). Average linear velocities for each station are estimated from monthly combinations of the campaign, BARD, PBO and IGS solutions and are shown in Figure 3.22. BAVU3β is still preliminary, but represents a substantial increase in data density over previous versions. A final BAVU3.0 will include even more campaign data collected recently and a closer integration with the BARD network.

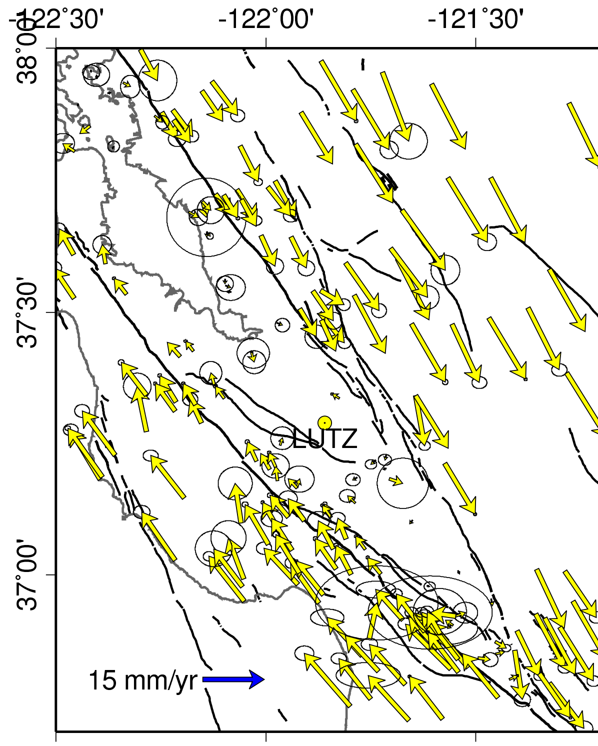

Figure 3.22: Velocities from BAVU3β, including BARD stations, as well as campaign and PBO stations. Yearly velocities are relative to station LUTZ, marked by a yellow circle.

ARRA infrastructure improvements

A major activity of the last two years has been work performed under the ARRA program to upgrade BARD infrastructure, including upgraded equipment at nearly half the BARD network stations and seven new stations. All receiver upgrades are now complete, though troubleshooting to ensure smooth operation of the new equipment is still on-going. During the course of the upgrades, site SBRN was decomissioned and has been officially replaced by site SBRB. SBRB was installed after vandalism at SBRN caused an extended data outage and has been running in tandem with SBRN for over a year. BSL engineers have also installed six new stations (GASB, JRSC, MCCM, MNRC, PTRO, and WDCB), all collocated with BDSN seismometers (or planned BDSN sites) and collecting and streaming data at 1 Hz.

Three types of monument design were used in the station installations. Stations JRSC and WDCB (and HELL) are short brace monuments, composed of four legs cemented into bedrock. A vault-mounted monument was used for three stations where there was adequate sky view directly above the seismic vault. The seismic vaults are large structures, framed by a shipping container and cemented to bedrock. The GPS antennas are mounted on pipe embedded in the vault wall, for this purpose, at the time of construction. These made them relatively cheap to install. Some work had previously been done to construct the monument at PTRO, so we continued the installation of a concrete post monument anchored to

	Sites	Lat. (deg.)	Lon. (deg)	Receiver	Telem. .	Sampling rate	Collocated Network	Location
1	BRIB	37.91	-122.15	NETRS	FR	1 Hz	BDSN	Briones Reservation, Orinda
2	CMBB	38.03	-120.39	NET-G3A	FR	1 Hz	BDSN	Columbia College, Columbia
3	DIAB	37.87	-121.92	NETRS	FR	1 Hz		Mt. Diablo
4	FARB	37.69	-123.00	NETRS	R-FR	1 Hz	BDSN	Farallon Island
5	GASB	39.65	-122.72	NET-G3A	R-FR	1 Hz	BDSN	Alder Springs, CA
6	HOPB	38.99	-123.07	NET-G3A	R-FR	1 Hz	BDSN	Hopland Field Stat., Hopland
7	JRSC	37.4	-122.24	NET-G3A	Int	1 Hz	BDSN	Jasper Ridge Biol. Preserve
8	LUTZ	37.28	-121.87	NET-G3A	FR	1 Hz	BDSN	SCC Comm., Santa Clara
9	MCCM	38.14	-122.88	NET-G3A	VSAT	1 Hz	BDSN	Marconi Conference Center
10	MHCB	37.34	-121.64	NETRS	FR	1 Hz	BDSN	Lick Obs., Mt. Hamilton
11	MHDL	37.84	-122.49	NETRS	R-FR	1 Hz	mini-PBO	Marin Headlands
12	MNRC	38.88	-122.44	NET-G3A	VSAT	1 Hz	BDSN	McLaughlin Mine, CA
13	MODB	41.90	-120.30	NETRS	VSAT	1 Hz	BDSN	Modoc Plateau
14	MONB	37.48	-121.87	NET-G3A	FR	1 Hz		Monument Peak, Milpitas
15	OHLN	38.00	-122.27	NET-G3A	FR	1 Hz	mini-PBO	Ohlone Park, Hercules
16	ORVB	39.55	-121.50	NET-G3A	FR	1 Hz	BDSN	Oroville
17	OXMT	37.49	-122.42	NET-G3A	FR	1 Hz	mini-PBO	Ox Mountain
18	PKDB	35.94	-120.54	NETRS	R-T1	1 Hz	BDSN	Bear Valley Ranch, Parkfield
19	PTRB	37.99	-123.01	NETRS	R-FR	1 Hz		Point Reyes Lighthouse
20	PTRO	36.39	-121.55	NET-G3A	FR	1 Hz		Potrero Hills
21	SAOB	36.76	-121.45	NETRS	FR	1 Hz	BDSN	San Andreas Obs., Hollister
22	SBRB	37.69	-122.41	NET-G3A	FR	1 Hz	mini-PBO	San Bruno Replacement
23	SODB	37.17	-121.93	NET-G3A	R-FR	1 Hz		Soda Springs, Los Gatos
24	SRB1	37.87	-122.27	NET-G3A	Fiber	1 Hz		Seismic Replace. Bldg., Berkeley
25	SUTB	39.20	-121.82	NETRS	R-FR	1 Hz	BDSN	Sutter Buttes
26	SVIN	38.03	-122.53	NET-G3A	R-FR	1 Hz	mini-PBO	St. Vincents
27	TIBB	37.89	-122.45	NET-G3A	R-Int	1 Hz		Tiburon
28	UCD1	38.53	-121.75	NETRS	Int	1 Hz		UC Davis, Davis
29	UCSF	37.75	-122.46	NET-G3A	FR	1 Hz		UC San Francisco, San Francisco
30	WDC	40.58	-122.54	NET-G3A	FR	1 Hz	BDSN	Whiskeytown Dam, Whiskeytown
31	YBHB	41.73	-122.71	NETRS	FR	1 Hz	BDSN	Yreka Blue Horn Mine, Yreka
32	HELL	36.68	-119.02				BDSN	Rademacher Property, Miramonte

Table 3.11: List of BARD stations maintained by the BSL. Two models of receiver are in operation: Trimble NetRS, (NETRS), Topcon Net-G3A (NET-G3A). The telemetry types are listed in column 6: FR = Frame Relay, R = Radio, VSAT= Satellite, Int = Internet, T1=T1 line, Fiber=direct fiber connection. Some sites are transmitting data over several legs with different telemetry.

the underlying substrate with cemented reinforcing rods. This is a type of monument we have used for other BARD stations (e.g. MONB), which has been shown to be stable.

All of the new monuments have performed well in the short time they have been operational; the longer-term stability of the monuments will need to be evaluated after 2-3 years. The average daily uncertainty is calculated from the formal error estimated independently by GAMIT/GLOBK during each day of processing. This quantity will be large if there is poor sky view and/or large amounts of multi-path at the site and for GASB, MCCM and WDCB, this value is higher than typical for BARD stations (Table 3.12). The time series RMS is a measure of the scatter in the cleaned time series and thus represents the short-term stability of the monument. All the new stations have RMS values on a par with those of existing BARD stations. Furthermore the stations with slightly higher RMS (GASB, MCCM, WDCB) are also those with higher average uncertainty, suggesting that their scatter results from their environment, rather than from monument instability. Indeed, these sites all have challenging sky view environments, but we nonetheless believe they are adequate based on the RMS values. Better nearby sites were not available for any of these stations and we were constrained in our ability to choose locations by the necessity of sharing telemetry with the BDSN station. On this short time scale, there is therefore no indication that the vault-mounted monuments are less stable than the short brace monuments. A further analysis when 2-3 years of data are available will show whether these monuments are stable over longer time periods and correctly reflect tectonic motion.

In addition to the equipment upgrades, the ARRA program also funded the re-establishment of daily processing and time-series generation for BARD backbone stations and upgrades to the BARD website. Daily processing ensures that bad data is caught quickly and problems can be fixed in a timely manner. Each day of data is processed twice, first with IGS Rapid orbit files within 24 hours of collection and again after IGS Final orbit files are available, using within 2-3 weeks. BARD rapid solutions are used to generate a new data point in the station displacement series right away and IGS global solutions and PBO network solutions are combined in when they are available and provide improved constraints to the time series. Final time series displacements are held until BARD final solutions, IGS, and PBO final network solutions are all available. Time series can be viewed and downloaded from the BARD website (`http://earthquakes.berkeley.edu/bard`).

	Time Series RMS			Avg Daily Uncert		
	N	E	U	N	E	U
New Monuments - Vault Mounted						
GASB	1.8	1.7	10	4.7	3.9	21.6
MCCM	1.8	2.3	10.9	5.3	6.5	29.3
MNRC	0.9	0.9	4.6	2.3	2.2	8.4
New Monuments - Short Brace						
JRSC	0.6	1	5.5	2.1	2	7.6
WDCB	1.7	1.7	7.5	6	4.9	22.4
New Monuments - Anchored Concrete Post						
PTRO	0.5	0.4	3	2.9	2.6	10.5
Existing Monuments						
BRIB	2.4	2.1	5.4	2.7	2.5	10.3
CMBB	0.8	1.4	5.4	3.6	3.7	13.9
DIAB	1.6	1.1	4.5	2.4	2.3	8.9
FARB	0.7	1.4	3.4	1.9	2	6.8
HOPB	1.5	1.3	10.1	3.2	3.1	13.6
LUTZ	2.4	1	3.8	2.3	2.3	8
MHCB	1.4	1.7	2.8	1.8	1.9	6.2
MHDL	1.8	2	9.5	3.3	3	12.5
MODB	1.4	1.6	7.1	3.3	3.2	12.4
MONB	0.8	1.3	3.3	2.1	2.1	7.2
OHLN	2.9	2.3	3.4	2.5	2.5	9.1
ORVB	0.9	1.3	7	2.4	2.3	8.5
OXMT	1.3	1.6	5.9	3	2.7	12.1
PKDB	1.7	1.1	4.4	2.9	2.9	11.3
PTRB	1.1	1.5	4	2.2	2.2	7.5
SAOB	1.2	1.2	3.3	2.3	2.4	8.3
SBRB	1.8	3.4	6.3	4.5	3.8	17.6
SODB	2.4	1.8	5.2	3.4	3.2	13.1
SRB1	3.8	1.2	4	2.7	2.5	9.9
SUTB	2.2	2.2	4.4	2.5	2.3	8.2
SVIN	0.9	1.3	4.3	2	1.9	7
TIBB	1.3	1.3	3.3	2.3	2.4	9
UCD1	1.4	1.8	12.6	2.3	2.3	8.2
UCSF	1.8	1.4	4.3	2.6	2.4	9.3
YBHB	2.8	3.9	7.7	2.9	2.6	10.6

Table 3.12: Table of results from short term site stability analysis. Time Series RMS is the RMS of the cleaned time series residuals after removing earthquake offsets and secular velocity and represents the repeatability of the station positions. Average daily uncertainty is the average formal error determined independently for each day by GAMIT/GLOBK.

Real-time data processing

A prototype system for processing BARD GPS data in real time had been established and will continue to be improved upon. We are using TrackRT, together with predicted orbits from the International GPS service (IGS) to produce high sample rate displacement time series with 2-3 second latency. TrackRT was developed at MIT and is based on GAMIT/GLOBK, which we use for daily processing. 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.

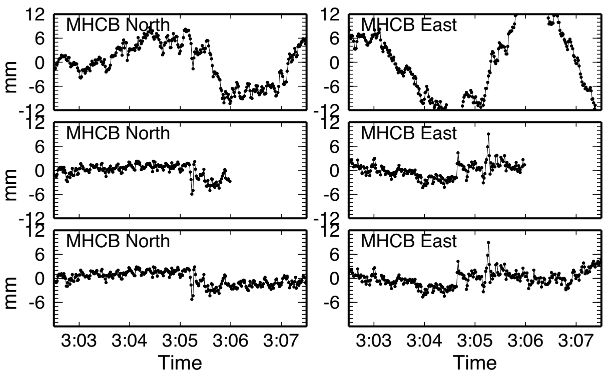

Figure 3.23: Time series of East and North motions for station MHCB during the M5.5 Alum Rock earthquake. The top row is simulated real-time data processing, the middle row is post-processing including up to a minute of data after the event origin time and the bottom row includes 10 minutes of post-earthquake data. Note that the plots are in GPS time, such that the earthquake origin time would plot as 3:05:09.

The scatter in the displacements 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. Nonetheless, the size of the scatter has implications for the size of earthquake for which GPS will be able to provide information in real time. Simulations of the moderately-sized 2007 M5.5 Alum Rock earthquake show that the time series produced in real time would have been very difficult to use to obtain static offsets (Figure 3.23). Post-processed time series, delayed by as little as 1 minute, produced cleaner time series and could have produced reasonable estimates of the static offsets (see Section 23). This implies that separate approaches should be taken for using GPS data for Earthquake Early Warning for large events and for using it for rapid response to moderate or large earthquakes.

5.3 Acknowledgements

The BARD program is overseen by Ingrid Johanson and Richard Allen. Bill Karavas, John Friday, Aaron Enright, Joshua Miller, Doug Neuhauser, Mario Aranha and Jennifer Taggart contributed to the operation of the BARD network in 2011-12. Operation of the BARD network is partially supported by funding from the USGS/NEHRP program grant #G10AC00141 and infrastructure upgrades were made possible by funding from the ARRA grant #G10AC00079. Real-time data processing is supported by a grant from the Moore Foundation.

5.4 References

d'Alessio, M. A., I. A. Johanson, R. Bürgmann, D. A. Schmidt, and M. H. Murray, Slicing up the San Francisco Bay Area: Block kinematics from GPS-derived surface velocities, *J. Geophys. Res., 110*, B06403, doi:10.1029/2004JB003496, 2005.

Herring, T., GLOBK: Global Kalman Filter: VLBI and GPS Analysis Program, version 10.2, 2005.

Houlié, N. and Romanowicz, B., Asymmetric deformation across the San Francisco Bay Area faults from GPS observations in northern California, *Phys. Earth Planet. In.*, in press.

King, R., and Y. Bock, Documentation of the GAMIT software, MIT/SIO, 1999.

6 Northern California Earthquake Data Center

6.1 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, pore pressure, water level, and wind speed sensors. Earthquake catalogs can include time, hypocenter, magnitude, moment tensor, 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 Earthquake Management Center (NCEMC), a component of the California Integrated Seismic Network (CISN). The CISN is the California regional organization of the Advanced National Seismic System (ANSS).

6.2 2011-2012 Activities

By its nature, data archiving is an ongoing activity. In 2011-2012, the NCEDC continued to expand its data holdings and enhance access to the data. Projects and activities of particular note include:

- Purchased SAN (Storage Area Network) storage and fibre channel switches to upgrade and expand the NCEDC data storage and archive systems.

- Developed and tested Web services for the distribution of station metadata using Station XML, waveform inventory, and MiniSEED data.

- Began receiving, archiving, and distributing event information (hypocenter, magnitude, phase, and amplitude data) and waveforms for the DOE Enhanced Geothermal Systems (EGS) monitoring project.

- Continued the process of reading and archiving continuous NCSN seismograms from tapes for 1993-1998.

- Continued to support the NCEMC earthquake analysis by providing real-time access to earthquake parameters and waveforms from the NCEDC for the CISN `Jiggle` earthquake review software.

- Completed work with the NCSN and USGS National Strong Motion Program (NSMP) to import the metadata and build dataless SEED volumes for all NSMP dialup stations.

- Began continuous data archiving from the LBNL Geysers Network, a dense network of 32 3-component stations acquiring data at 500 samples/second to monitor the California Geysers geothermal region.

6.3 Data Types and Contributors

Table 3.13 and Figure 3.24 provide a breakdown of the NCEDC data by data type. Figure 3.25 shows the total data volume by year as itemized in Table 3.13.

BDSN/NHFN/mPBO Seismic Data

The BDSN (Operational Section 1), NHFN (Operational Section 3), and Mini-PBO (Operational Section 3) stations (all network code BK) send real-time data from 50 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 most of the NHFN borehole seismic data channels. All timeseries 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 upgrades 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

NCSN continuous waveform data are transmitted from USGS/Menlo Park in real time to the NCEDC via the Internet, converted to MiniSEED, and made available to users immediately through the NCEDC DART. NCSN event waveform data, as well as data from all other real-time BSL and collaborating networks, are automatically

Data Type	GBytes
BDSN/NHFN/mPBO (broadband, electric and magnetic field, strain) waveforms	8,203
NCSN seismograms	30,118
Parkfield HRSN seismograms	3,877
GPS (RINEX and raw data)	2,933
UNR Nevada seismograms	1,580
SCSN seismograms	2,791
Calpine/Unocal Geysers region seismograms	38
EarthScope SAFOD seismograms	2,119
EarthScope USArray seismograms	281
EarthScope PBO strain and seismic waveforms	2,949
PG&E seismograms	688
USGS low frequency geophysical waveforms	3
Misc data	3,245
Total size of archived data	58,825

Table 3.13: Volume of Data Archived at the NCEDC by network.

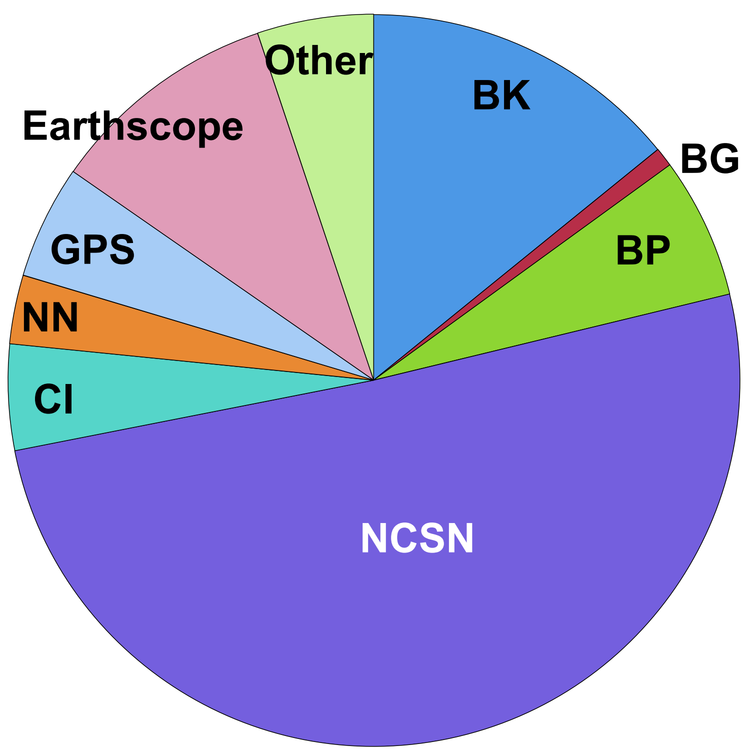

Figure 3.24: Chart showing the relative proportion of each data set at the NCEDC. BK - Berkeley Digital Seismic Network; BP - Berkeley High-resolution Seismic Network in Parkfield; NCSN - Northern California Seismic Network and collaborators; CI - Southern California Seismic Network; NN - University of Nevada, Reno Seismic Network; GPS - various GPS datasets, including BARD; EarthScope - data from various EarthScope activities; Other - various small data sets.

collected by the NCEMC waveform archiver and stored at the NCEDC for event review and analysis and for distribution to users. All NCSN and NCEMC 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 finished the first phase of the NCSN tape continuous waveform archiving for the data from 1996 to early 2006, and have continued the project this year by processing and archiving NCSN tape data from 1993 through 1996.

Parkfield High Resolution Seismic Network 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) Strain Data

The NCEDC is 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, and 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.

EarthScope SAFOD

The NCEDC is 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 4 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, are available in real-time from the NCEDC DART, 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.

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. Through a collaboration with Dr. Simon Klemperer at Stanford

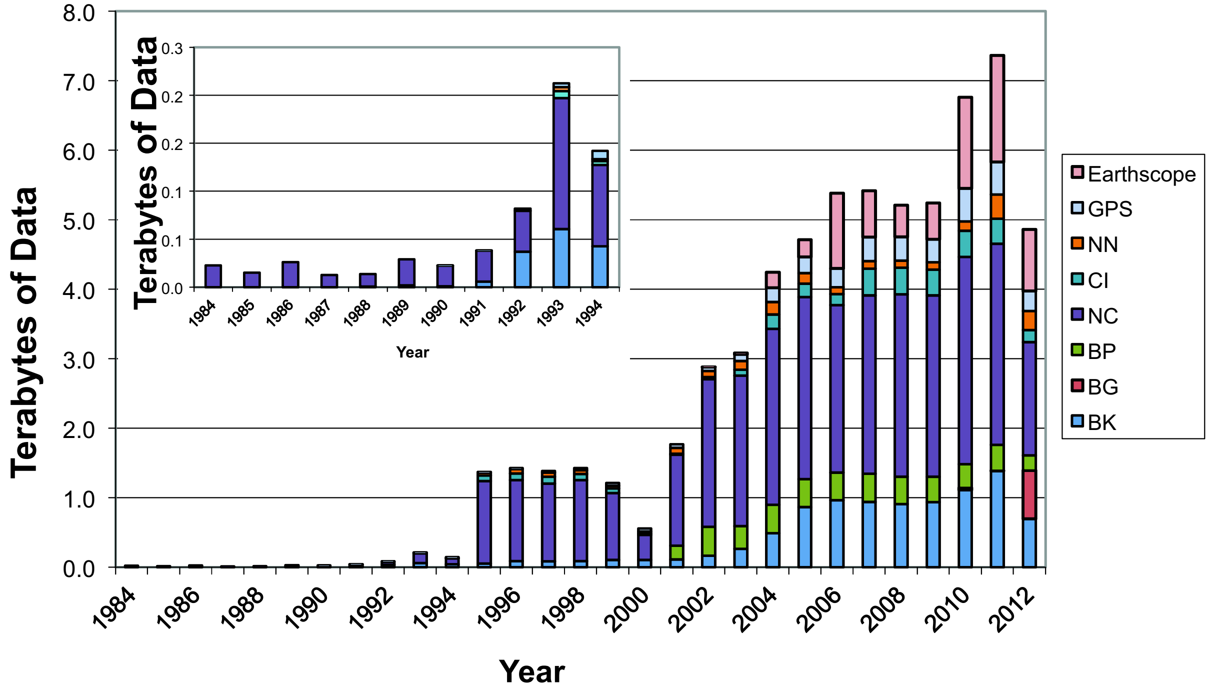

Figure 3.25: Figure showing the total volume of data archived at the NCEDC, broken down by data year.

University, 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). The NCEDC GPS daily archive now includes 80 continuous sites in Northern California. Of these, there are $\sim$ 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/MP, the BSL is now streaming real-time 1 Hz continuous data from 42 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 Calpine Corporation operated a micro-seismic monitoring network in the Geysers region of Northern California. Prior to 1999, this network was operated by Unocal. 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 that were recorded by the Calpine/Unocal Geysers network and are available via research accounts at the NCEDC.

The Lawrence Berkeley National Laboratory (LBNL), with funding from the California Energy Commission, currently operates a 32 station network in the Geysers region with an emphasis on monitoring seismicity related to well water injection. The earthquake locations and waveforms from this network are sent to the NCEDC, and the locations are forwarded to the NCSN so that they can be merged into the NCSN earthquake catalog. In August 2007, the NCSN installed an Earthworm system at the Geysers to receive continuous LBNL Geysers data, and this system provides event waveforms for events detected by the NCEMC real-time earthquake monitoring and processing system and the corresponding event data archive at the NCEDC. The event data from LBNL Geysers event waveforms collected from April 2004 to August 2007 will be associated with events from the NCSN catalog and will be included with the existing waveforms for these events. In March 2012, the NCEDC began to receive continuous data from the stations in near real-time, and began archiving these continuous data.

DOE Enhanced Geothermal Monitoring (EGS) Data

Starting in 2010-2011, BSL was funded through LBNL to archive and disseminate seismic event parameters and corresponding waveform timeseries from monitoring networks operated under the auspices of the US Department of Energy Geothermail Monitoring Program. We have collected and verified the station metadata for these networks, and populated the data into the database. This year we began to receive and archive the event data and waveforms from these networks. The timeseries 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.

USGS Low Frequency Data

Since 1974, the USGS at Menlo Park, in collaboration with other principal investigators, has collected an extensive low-frequency geophysical data set that contains over 1300 channels of tilt, tensor strain, dilatational strain, creep, magnetic field, 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, 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 MiniSEED 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 timeseries data from 887 data channels from 167 sites, and have instrument response information for 542 channels at 139 sites. The waveform archive is updated on a daily basis with data from 350 currently operating data channels.

The USGS is reducing support for these stations, and the network is being slowly retired. The NCEDC continues to receive and archive the data channels that are being provided by the USGS.

SCSN/Statewide Seismic Data

In 2004, the NCEDC started to archive broadband and strong motion data from 15 SCSN (network CI) stations that are telemetered to the Northern California Earthquake Management Center (NCEMC) of the California Integrated Seismic Network (CISN). These data are 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 9.

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

With the demise of the CNSS and the development of the 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. We continue to create, house, distribute, and provide a searchable Web interface to the ANSS composite catalog, and to aid the regional networks in submitting data to the catalog.

6.4 NCEDC Operations

The current NCEDC facilities consist of a mass storage environment hosted by a 8-core Sun X4150 computer, a 100 slot LTO3 tape library with two tape drives and a 20 TByte capacity, and 180+ TBytes of RAID storage, all managed with the SAM-FS hierarchical storage management (HSM) software. Four additional 8-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.

In 2005, the NCEDC relocated its archive and distribution system from McCone Hall to a new state-of-the-art computer facility 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 entire facility is powered by a UPS with generator backup.

In 2008-2009, the tape library was upgraded from LTO2 to LTO3 drives, and all online tape data was rearchived on LTO3 tapes. DLT tape libraries are used to read NCSN continuous data tapes.

In 2011-2012, the NCEDC data archive grew to exceed the NCEDC online disk capacity. We acquired a new SAN disk storage system that provides the NCEDC with 90 TB of primary online storage and 90 TB of SAMFS cache to improve filesystem performance. We migrated all of the waveform and GPS archive data to the new SAN storage. In addition, we upgraded the fibre channel switches to support the 8 Gbit/second interfaces of the new SAN disk system and computer interfaces.

The SAMFS hierarchical storage management (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 LTO3 tape (of which the most recent data are stored online in the tape library), and a third copy on LTO2 tape which is stored offline and offsite. In addition, all SAMFS data are stored in an online disk cache which 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 an network-accessible structured filesystem to support realtime access to current and recent timeseries 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. The DART waveforms can be accessed by users from Web browsers or command-line programs such as *wget*, or through NCEDC data services described in the data distribution section of this document.

We use the IRIS ringserver software as the primary method for delivering real-time data to the DART. The ringsever 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 orbserver. Clients running at the NCEDC computer connect to remote servers at the BSL, USGS/Menlo Park, and UNAVCO, retrieve the MiniSEED timeseries data records, and write them to daily channel files in the NCEDC DART. Strain data from the EarthScope PBO network are delivered to the NCEDC using SeedLink and are inserted into the DART using a similar SeedLink client program.

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 a 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,
- 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 timeseries plots for state-of-health data channels,
- optional timing corrections for data,
- optional extraction of event-based waveforms from continuous data channels,
- optional repacking of MiniSEED data,
- creating waveform inventory entries in the NCEDC database,
- publishing the data for remote access on the NCEDC.

Calqc 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/MP NCSN, and other seismic stations used by the NCEMC. BSL staff currently chairs 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 2011-2012 year include new sets for associating strong ground motion observations with events, merging of channel table tables for real-time and post-processing applications, and adding additional event types to describe a wider range of earth motions.

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

PSD and PDF

Changes in the seismic noise recorded at a site in the absence of earthquakes may be an indication of instrumental or other problems. Thus, the regular review of the noise is a useful tool for evaluating station performance and quality. Programs developed by Dan McNamara and Ray Buland at the USGS use a probability density function (PDF) to compute the distribution of seismic power spectral density (PSD) on a daily basis. The results are aggregated into weekly and yearly plots for each data channel.

The NCEDC computes daily PDFs for all high-rate seismic and strain channels from the Berkeley networks, and for many of the data channels of the NCSN network and other networks that contribute to the operation of the NCEMC. The NCEDC noise analysis plots are available at `http://www.ncedc.org/ncedc.PDF/`

6.5 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 the domain name *ncedc.org*. The NCEDC's Web address is `http://www.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 and first motion mechanisms 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 20,891 data channels from 2,315 stations in 23 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. In collaboration with the USGS NCSN and the NSMP (National Strong Motion Program), the NCEDC is building the metadata and dataless SEED volumes for over 700 stations and 4700 data channels of the NSMP dialup stations. Station metadata can be acquired by downloading pre-assembed dataless SEED files, using NetDC to request metadata by station, channel and time, or by new NCEDC Web services.

Web Services

The NCEDC developed and deployed five Web services for distributing both timeseries and related channel metadata. Web services use standard web HTTP protocol for sending requests and receiving data. Web services can be used interactively from a web browser, or can be easily called from scripts and user programs. These Web services are compatible with the corresponding IRIS DMC Web services. These new data services are:

ws-station - provides station and channel metadata in StationXML format.

ws-resp - provides channel instrument response in RESP format.

ws-availability - returns information about what time series data is available at the NCEDC archive.

ws-dataselect - returns a single channel of time series data in miniSEED format from the NCEDC archive.

ws-bulkdataselect - returns multiple channels of time series data in miniSEED format for specified time ranges.

StationXML is an XML (Extensible Markup Language) schema designed for sharing station metadata. StationXML was originally designed at the SCEDC and is now maintained in collaboration with NCEDC, IRIS, and NEIC. RESP format is the ascii channel response format created by the IRIS rdseed program, and supported by programs such as evalresp. Documentation on Station XML is available at `http://www.data.scec.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 timeseries 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 is currently operational 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.

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 has 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.

SWC and SWS

UC Berkeley developed the Simple Wave Server *swc* and Simple Wave Client *sws* 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.

6.6 Metrics for 2011-2012

- Distributed over 7,075 GB of waveform, GPS, and earthquake catalog data to external users.

- NCEDC uptime for data delivery was over 99.5% for the year.

- Tables 3.14 and 3.15 show the percentage of data archived as a percentage of the station operational time for BSL stations based on the highest rate vertical data channel for each station. If channels were renamed during the year due to equipment upgrades, or we operated multiple data loggers at the site, there may be multiple entries for that site.

Net	Sta	Cha	Loc	%Archived
BP	CCRB	DP1	–	24.12%
BP	CCRB	DP1	40	99.80%
BP	EADB	DP1	–	99.70%
BP	EADB	DP1	40	99.98%
BP	FROB	DP1	40	99.91%
BP	GHIB	DP1	–	97.64%
BP	GHIB	DP1	40	99.90%
BP	JCNB	DP1	–	0.00%
BP	JCNB	DP1	40	99.95%
BP	JCSB	DP1	40	99.97%
BP	LCCB	DP1	–	26.50%
BP	LCCB	DP1	40	99.93%
BP	MMNB	DP1	40	100.00%
BP	RMNB	DP1	–	100.00%
BP	SCYB	DP1	–	97.96%
BP	SCYB	DP1	40	100.00%
BP	SMNB	DP1	40	99.93%
BP	VARB	DP1	40	99.98%
BP	VCAB	DP1	40	99.89%

Table 3.14: Percentage of Continuous Data Archived for BP stations based on station operation time for the year.

6.7 Acknowledgements

The NCEDC is a joint project of the BSL and the USGS Menlo Park and is funded primarily by BSL and USGS Cooperative Agreements G10AC00141 and G10AC00093. Additional funding for the processing and archiving of the EarthScope PBO and SAFOD data were provided by EarthScope subawards EAR0732947-07 through UNAVCO. Archival of geothermal monitoring data are provided through LBNL project number 6948613.

Douglas Neuhauser is the manager of the NCEDC. Stephane Zuzlewski, Mario Aranha, Ingrid Johanson, Taka'aki Taira, Jennifer Taggart, Clay Miller, and Peggy Hellweg of the BSL and David Oppenheimer, Hal Macbeth, Lynn Dietz, and Fred Klein of the USGS Menlo Park contribute to the operation of the NCEDC. Doug Neuhauser and Peggy Hellweg contributed to the preparation of this section.

Net	Sta	Cha	Loc	%Archived
BK	BDM	HHZ	00	100.00%
BK	BKS	HHZ	00	100.00%
BK	BL67	HHZ	00	52.17%
BK	BL88	HNZ	00	99.69%
BK	BRIB	DP1	40	99.99%
BK	BRIB	HHZ	00	100.00%
BK	BRK	HHZ	00	100.00%
BK	CMAB	DP1	–	97.98%
BK	CMAB	DP1	40	99.99%
BK	CMB	HHZ	00	100.00%
BK	CVS	HHZ	00	100.00%
BK	FARB	HHZ	00	99.99%
BK	GASB	HHZ	00	84.58%
BK	HAST	HHZ	00	100.00%
BK	HATC	HHZ	00	100.00%
BK	HELL	HHZ	00	100.00%
BK	HERB	DP1	–	100.00%
BK	HOPS	HHZ	00	99.84%
BK	HUMO	HHZ	00	100.00%
BK	JCC	HHZ	00	100.00%
BK	JRSC	HHZ	00	100.00%
BK	KCC	HHZ	00	99.93%
BK	MCCM	HHZ	00	99.91%
BK	MHC	HHZ	00	100.00%
BK	MHDL	EP1	40	100.00%
BK	MNRC	HHZ	00	100.00%
BK	MOBB	BHZ	00	98.71%
BK	MOD	HHZ	00	100.00%
BK	OHLN	EP1	40	99.95%
BK	ORV	HHZ	00	100.00%
BK	OXMT	LP1	40	99.98%
BK	PACP	HHZ	00	99.66%
BK	PETB	EP1	40	99.71%
BK	PKD	HHZ	00	99.98%
BK	RAMR	HHZ	00	100.00%
BK	RB2B	DP1	–	99.67%
BK	RFSB	CN1	40	99.36%
BK	RFSB	HNZ	00	100.00%
BK	SAO	HHZ	00	100.00%
BK	SBRN	EP1	40	99.73%
BK	SCCB	HNZ	00	100.00%
BK	SM2B	DP1	40	100.00%
BK	SUTB	HHZ	00	93.92%
BK	SVIN	EP1	40	99.81%
BK	THIS	HHZ	00	96.44%
BK	TSCN	HHZ	00	99.20%
BK	VAK	HHZ	00	100.00%
BK	VALB	EP1	–	100.00%
BK	WDC	HHZ	00	100.00%
BK	WENL	HHZ	00	99.98%
BK	YBH	HHZ	00	99.31%
BK	YBH	HHZ	50	100.00%

Table 3.15: Percentage of continuous data archived for BK stations based on station operation time for the year.

7 Data Acquisition and Quality Control

7.1 Introduction

Stations from the networks operated by the BSL transmit data continuously to the BSL facilities on the UC Berkeley campus for analysis and archival. In this section, we describe activities and facilities which pertain to the individual networks described in Operational Sections 1, 3, and 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 or activities which are specific to 2011-2012.

7.2 Data Acquisition Facilities

The computers and the associated telemetry equipment are located in the campus computer facility in Warren Hall at 2195 Hearst Avenue. This building was constructed to current "emergency grade" seismic codes and is expected to be operational even after a M 7 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.

7.3 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 3.26). 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 `comserv` and `qmaserv` developed by Quanterra for central data acquisition. These programs receive data from remote Quanterra 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, and other programs such as the seismic alarm process, the DAC480 system, and the feed for the Memento Mori Web page. Data from the TremorScope stations are acquired using the program `scream`. We are currently developing procedures to feed them into realtime analysis and to archive them.

The two computers performing data acquisition are also "network services" computers that reduce waveforms for processing with the AQMS software (Figure 3.27). To facilitate processing, each system maintains a shared memory region containing the most recent 30 minutes of data for each channel.

In the past, BDSN data loggers which use frame relay telemetry were configured to enable data transmission simultaneously to two different computers over two different frame relay T1 circuits to UCB. Normally, only one of these circuits was enabled. Unfortunately, we had to discontinue the second T1 circuit to which we had subscribed, because of decreases in funding from the State. The `comserv/qmaserv` client program `cs2m` receives data and multicasts it over a private ethernet. The program `mcast`, a modified version of Quanterra's `comserv` program, receives the multicast data from `cs2m`, and provides a comserv-like interface to local comserv clients. Thus, each network services computer has a `comserv/qmaserv` server for all stations, and each of the two systems has a complete copy of all waveform data.

We have extended the multicasting approach to handle data received from other networks such as the NCSN and UNR (University of Nevada, Reno). These data are received by Earthworm data exchange programs and are then converted to MiniSEED and multicast in the same manner as the BSL data. We use `mserv` on both network services computers to receive the multicast data and handle it in the same way as the 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 current information such as time quality, mass positions, and battery voltage and allows it to be displayed. If the parameter departs from the nominal range, the station is marked with yellow or red to indicate a possible problem.

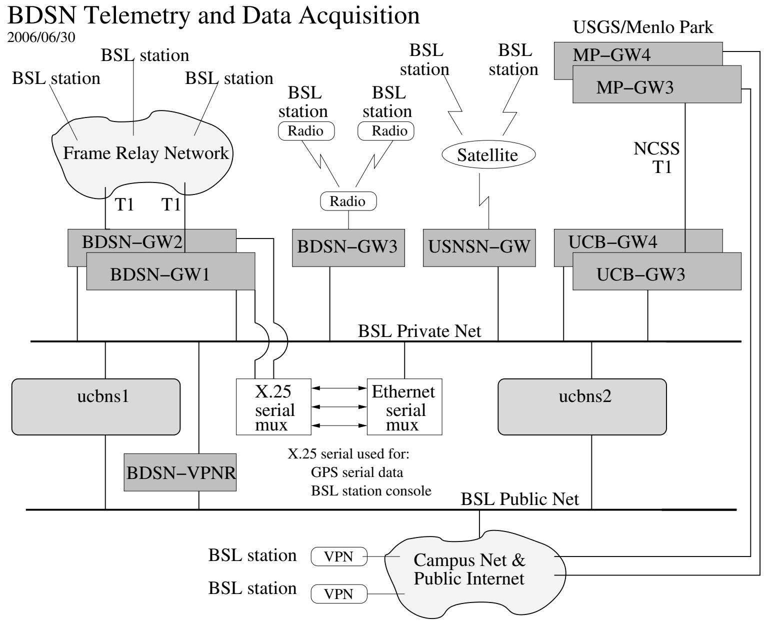

Figure 3.26: Data flow from the BDSN, NHFN, mPBO, HRSN, and BARD networks into the BSL central processing facility.

7.4 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 11, 2012, M 8.6 earthquake off the coast of northern Sumatra to check noise levels at our STS1 stations in the frequency band from 0.2 mHz to 2 mHz, by looking at the normal mode spectra (see Operational Section 1).

PSD Noise Analysis

The estimation of the Power Spectral Density (PSD) of the ground motion recorded at a seismic station, as documented in the 2000-2001 BSL annual report (`http://earthquakes.berkeley.edu/annual_report/`) provides an objective measure of background seismic noise characteristics over a wide range of frequencies. It also provides an objective measure of seasonal variation in noise characteristics and supports early diagnoses of instrumental problems. In the early 1990s, a PSD estimation algorithm was developed at the BSL for characterizing the background seismic noise and as a tool for quality control. The algorithm generates a bar graph output in which all the BDSN broadband stations can be compared by component. We also use the weekly PSD results to monitor trends in the noise level at each station. Cumulative PSD plots are generated for each station and show the noise level in 5 frequency bands for the broadband channels. The plots make it easier to spot certain problems, such as failure of a sensor. In addition to the station-based plots, a summary plot is produced for each channel. The figures are presented as part of a noise analysis of the BDSN on the web at `http://www.earthquakes.berkeley.edu/seismo/bdsn/psd/`.

PDF PSD Noise Analysis

In addition to the PSD analysis developed by Bob Uhrhammer, the BSL has implemented 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 includes earthquakes, calibration pulses, and cultural noise.

This is in contrast to Bob Uhrhammer's PSD analysis, which looks 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 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, strain meters, and electric and magnetic field sensors. These 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 newly upgraded webpage at `http://www.ncedc.org/ncedc/PDF/`. In addition to accessing the PDF plots for each component at a station, the entry page now provides summary figures of the noise at each station, so they can be reviewed quickly. To provide an overview, we have developed summary figures for all components in two spectral bands, 32 - 128 s and 0.125 - 0.25 s for broadband sensors, and

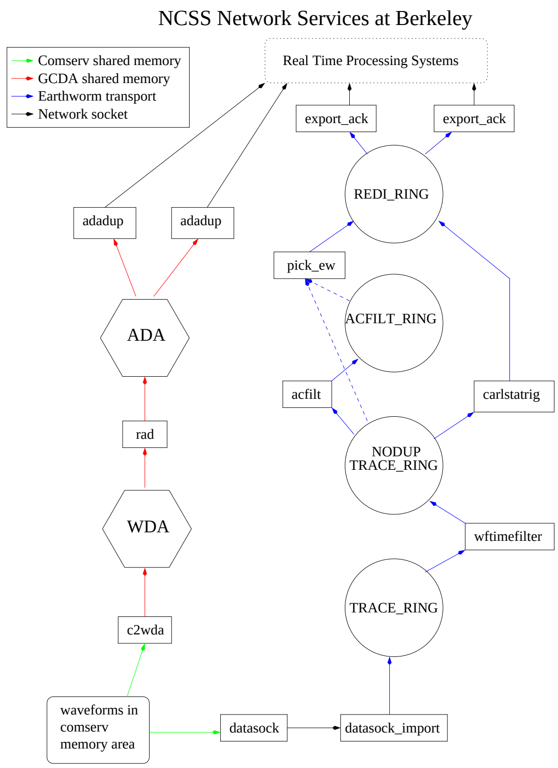

Figure 3.27: Flow of data from `comserv/qmaserv` areas through network services processing. One stream of the network services provides picks (and currently still provides codas) determined using the programs shown in the right flow path. Every 5 seconds, ground motion parameters are also determined, 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.

only in the short period band for other short period sensors. The figures are also available on the web at `http://www.ncedc.org/ncedc/PDF/`.

7.5 Sensor Testing and Calibration

The BSL has an Instrumentation Test Facility in the Byerly Seismographic Vault where the characteristics of up to eight sensors can be systematically determined and compared. The test equipment consists of an eight-channel Quanterra Q4120 high-resolution data logger 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 sensor testing facility of the BSL is described in detail in the 2001-2002 Annual Report (`http://www.earthquakes.berkeley.edu/`).

Borehole Geophone Calibration Analysis

Borehole geophones can be calibrated as described in last year's annual report. If there are several sensors at a site, calibration can also procede by comparing data from two sensors with similar orientation. The NHFN borehole station CMAB, for example, is equipped with OYO Geospace GS-11 geophones and Wilcoxon 731A accelerometers. Data from co-sited geophone and strong-motion sensors allow us to verify the instrument response of the sensors. Assuming the accelerometer response is flat in a frequency band analyzed (e.g., 1-10 Hz), we determine and verify the instrument response of the geophones.

We compared the ground motion observed from the geophones with the corresponding ground motions inferred from the co-sited accelerometers for the 5 March 2012 Mw 4.0 El Cerrito local earthquake (Figure 3.28). Using the instrument response from the factory calibration sheet (the sensor sensitivity of 50 V/m/s, the natural period of 0.2222 sec or 4.5 Hz, and the fraction of critical damping of 0.62), we observed the amplitude and phase discrepancies in a 1-10 Hz band between the geophone and strong-motion data (gray lines in Figures 3.28d and 3.28e). These observed discrepancies indicate that the sensor sensitivities of the accelerometers and geophones, and the natural periods and fractions of critical damping of the geophones need to be updated. Assuming that the sensor sensitivities of the accelerometers in the factory calibration sheet are correct, we determine the geophone sensor sensitivities, natural periods, and fraction of critical dampings by using a grid search approach that finds the solution minimizing the variance between the inferred ground motions from the geophones and the accelerometers in each component. For example, we find the sensitivity vertical geophone component at CMAB to be 42.805 V/m/s, its natural period 0.2288 sec and its fraction of critical damping 0.67. Using the instrument responses determined in our analysis, the inferred ground motions from the geophones in individual components agree with those from the accelerometers (solid lines in Figures 1d and 1e).

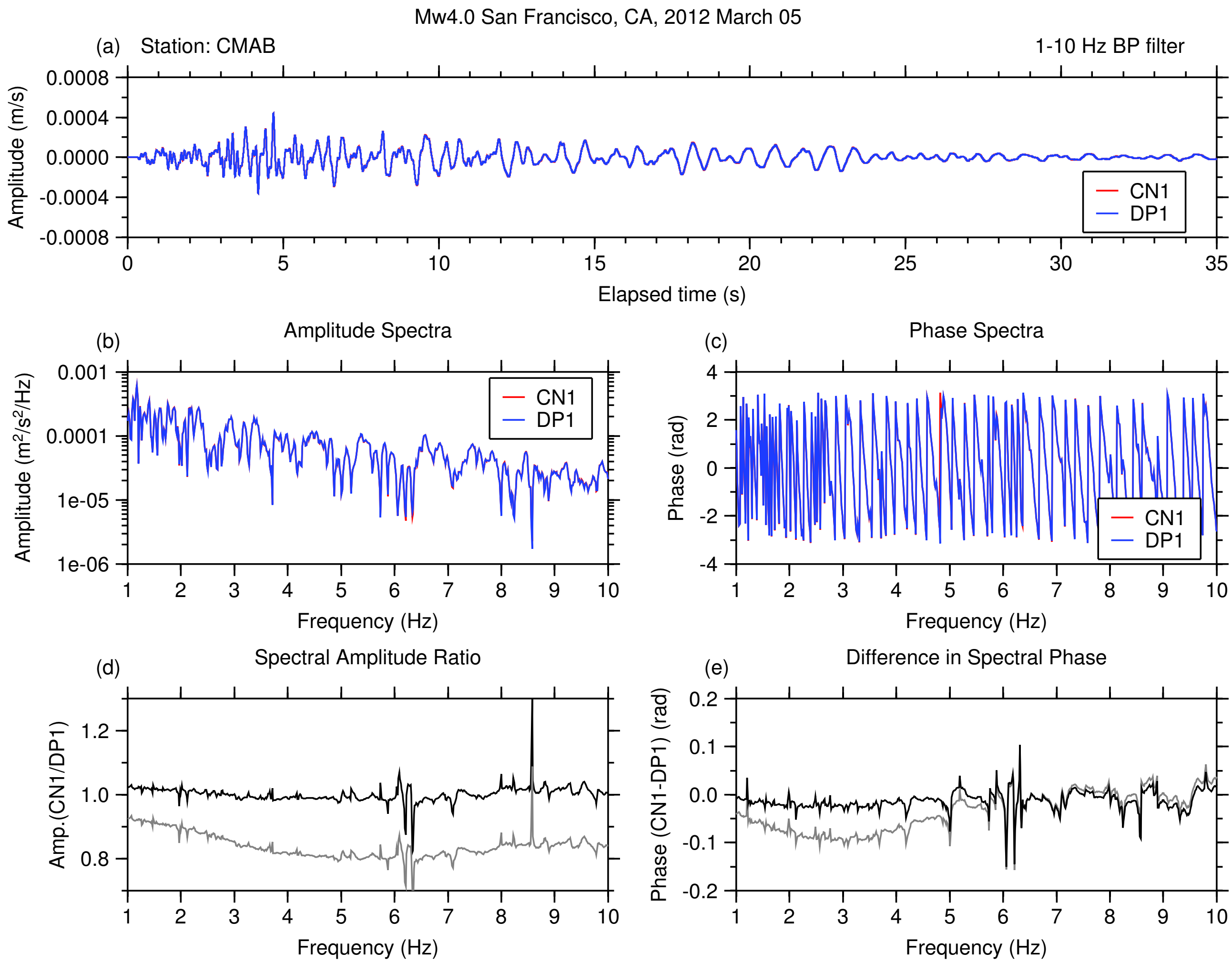

Figure 3.28: Example of the CMAB geophone data with the instrument response determined through our analysis. (a) Observed ground velocity from the CMAB geophone (blue) and accelerometer (red) in the vertical component with a 1-10 Hz bandpass filter. (b) Amplitude and (c) phase spectra of the data shown in (a). (d) Spectral amplitude ratio and (e) difference in spectral phase for the geophone and strong-motion data. Solid lines are the results with the instrument response determined by our analysis while gray lines are results with the instrument responses based on the factory calibration sheet.

7.6 STS-1/E300 Calibration Analysis

Introduction

E300 electronics packages have now been installed as replacement electronics for the STS-1s at BDSN stations CMB, BKS, HOPS, KCC and YBH. The Metrozet STS-1/E300 is an advanced electronics package that is a direct replacement for the original Streckeisen feedback electronics boxes. It matches the analog performance of the original electronics and provides enhancements to facilitate the installation and operation of the STS-1 seismometers in a modern seismic network. In particular, it provides digital control of all seismometer parameters, recentering, and state of health parameters, and it has auxiliary analog and digital input lines. All the control and diagnostic functions can be controlled either locally or remotely via ethernet. For a detailed description of the determination of the response of the STS-1/E300 seismometer system, see the Annual Report of 2010-2011.

Monitoring and Evaluating Instrument Response of the STS-1/E300 Systems in the BDSN

After the data logger for the CTBT STS-2 was reinstalled at YBH, we noticed that the response of the STS-1/E300 at that site had changed. As a result, we decided to regularly calibrate the STS-1/E300 combinations installed in the BDSN. At KCC, the E300 does not respond to remote commands, likely due to moisture that entered the cables at splices. We plan to replace those cables with a factory prepared set. In the meantime, we calibrated the other STS-1/E300 systems shortly after their original installations, and again in February 2012. Results are shown in Table 3.16.

7.7 Acknowledgements

Doug Neuhauser, Bob Uhrhammer, Taka Taira, Peggy Hellweg, Pete Lombard, Jennifer Taggart, Tom Weldon and Clay Miller are involved in the data acquisition and quality control of BDSN/HRSN/NHFN/mBPO data. Development of the sensor test facility and analysis system was a collaborative effort of Bob Uhrhammer, Tom McEvilly, John Friday, and Bill Karavas. IRIS (Incorporated Research Institutions for Seismology) and DTRA (Defense Threat Reduction Agency) provided, in part, funding for and/or incentive to set up and operate the facility, and we thank them for their support. Bob Uhrhammer, Taka Taira, Peggy Hellweg, Pete Lombard, Doug Neuhauser and John Friday contributed to the preparation of this section.

7.8 References

McNamara, D. and R. Buland, Ambient Noise Levels in the Continental United States *Bull. Seism. Soc. Am.*, 94, 4, 2004.

Rodgers, P.W., A.J. Martin, M.C. Robertson, M.M. Hsu and D.B. Harris, Signal-coil calibration of electromagnetic seismometers, *Bull. Seism. Soc. Am., 85,* 845-850, 1995.

Calibration Date	Stn	Cmp	Ts	hs	fg	hg	Calibration Date	Stn	Cmp	Ts	hs	fg	hg
2011.235	BKS	Z	359.8	0.715	12.38	0.437	2010.117	HOPS	Z	391.6	0.732	14.98	0.350
			-3.8%	-3.6%	0.5%	4.6%				-0.6%	0%	6.1%	3.1%
2012.040	BKS	Z	346.2	0.689	12.44	0.457	2012.039	HOPS	Z	389.1	0.732	15.89	0.361
			0.6%	0.3%	0%	0.9%				-0.4%	-0.7%	-0.1%	0%
2012.122	BKS	Z	348.2	0.691	12.44	0.461	2012.128	HOPS	Z	387.5	0.727	15.88	0.361
			0.1%	0.1%	-2.8%	-1.3%				0.8%	0.8%	-0.3%	-1.1%
2012.256	BKS	Z	348.4	0.692	12.09	0.455	2012.254	HOPS	Z	390.6	0.733	15.83	0.357
2011.235	BKS	N	360.7	0.716	17.10	0.336	2010.117	HOPS	N	391.9	0.740	16.17	0.326
			-3.8%	-2.5%	-0.8%	0%				1.2%	3.5%	3.9%	7.1%
2012.040	BKS	N	347.1	0.698	16.96	0.336	2012.039	HOPS	N	396.5	0.766	16.80	0.349
			0.7%	0.9%	0.9%	0%				-0.4%	-0.4%	1.8%	-4.3%
2012.122	BKS	N	349.4	0.704	17.11	0.336	2012.128	HOPS	N	394.8	0.763	17.11	0.334
			0%	-1.0%	-0.4%	0.3%				0.9%	1.3%	-0.4%	0%
2012.256	BKS	N	349.3	0.697	17.05	0.337	2012.254	HOPS	N	398.4	0.773	17.05	0.334
2011.235	BKS	E	360.5	0.722	13.19	0.400	2010.117	HOPS	E	392.4	0.731	15.85	0.339
			-4%	-4.3%	0.8%	5.2%				-1.4%	-1.6%	6%	2.9%
2012.040	BKS	E	346.1	0.691	13.30	0.421	2012.039	HOPS	E	387.1	0.719	16.80	0.349
			0.5%	-0.3%	-0.1%	0.2%				-0.5%	-0.7%	-0.1%	-1.7%
2012.122	BKS	E	347.9	0.689	13.29	0.422	2012.128	HOPS	E	385.3	0.714	16.79	0.343
			0.2%	1.0%	0%	-1.9%				0.6%	0.8%	-0.5%	1.2%
2012.256	BKS	E	348.5	0.696	13.29	0.414	2012.254	HOPS	E	387.7	0.720	16.70	0.347
2011.012	CMB	Z	365.7	0.731	12.91	0.461	2011.160	YBH	Z	371.5	0.731	11.94	0.465
			-0.1%	1.6%	2%	1.1%				-2%	-3.6%	1.9%	1.7%
2012.041	CMB	Z	365.4	0.743	13.17	0.466	2012.038	YBH	Z	364.0	0.705	12.17	0.473
			-0.3%	-0.3%	0.3%	0.2%				0%	-0.1%	-0.1%	-0.2%
2012.123	CMB	Z	364.4	0.741	13.21	0.467	2012.124	YBH	Z	364.1	0.704	12.16	0.472
			0.1%	-3.9%	0.7%	-1.9%				0.2%	0.1%	0%	-0.2%
2012.255	CMB	Z	364.9	0.712	13.12	0.458	2012.255	YBH	Z	365.0	0.705	12.16	0.471
2011.012	CMB	N	365.4	0.714	17.11	0.335	2011.160	YBH	N	370.2	0.736	13.12	0.418
			-0.3%	-1%	1.9%	-7.8%				-1.5%	-1.5%	-0.8%	5.7%
2012.041	CMB	N	364.3	0.707	17.43	0.309	2012.038	YBH	N	364.6	0.725	13.01	0.442
			0.2%	0.4%	-0.1%	4.2%				0.1%	-0.1%	-0.5%	-3.6%
2012.123	CMB	N	365.1	0.710	17.42	0.322	2012.124	YBH	N	365.0	0.724	12.95	0.426
			0.2%	3.2%	-.5%	1.2%				0.1%	1.1%	0.3%	2.6%
2012.255	CMB	N	366.0	0.733	17.33	0.326	2012.255	YBH	N	365.2	0.732	12.99	0.437
2011.012	CMB	E	365.0	0.718	13.31	0.425	2011.160	YBH	E	389.0	1.019	12.76	0.430
			-0.4%	-2.8%	1.7%	9.4%				11.7%	28.9%	4.8%	-4.4%
2012.041	CMB	E	363.5	0.698	13.53	0.465	2012.038	YBH	E	434.6	1.313	13.37	0.411
			0.4%	1.4%	-1.3%	-29%				1.8%	5.6%	0%	1.9%
2012.123	CMB	E	365.1	0.708	13.35	0.330	2012.124	YBH	E	442.3	1.386	13.37	0.419
			0.4%	0.1%	2.9%	33.3%				10.9%	0.2%	-0.1%	-9.1%
2012.255	CMB	E	366.4	0.709	13.74	0.440	2012.255	YBH	E	490.7	1.389	13.36	0.381

Table 3.16: Initial calibration, February 2012 calibration, May 2012 calibration, and September 2012 calibration for STS-1/E300 units at BKS, CMB, HOPS and YBH. Percentages indicate change in response between the two dates.

8 Northern California Earthquake Monitoring

8.1 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). This system determined earthquake parameters rapidly, producing near real-time locations and magnitudes of Northern and Central California earthquakes, estimates of the rupture characteristics and the distribution of ground shaking following significant earthquakes, and tools for the rapid assessment of damage and estimation of loss.

A short time later, in 1996, the BSL and the USGS began a collaboration for reporting on 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). The USGS and the BSL are now joined as the Northern California Earthquake Management Center (NCEMC) of the California Integrated Seismic Network (Operational Section 2).

With partial support from the USGS, the BSL is currently also participating in the development and assessment of a statewide demonstration system for warning of imminent ground shaking in the seconds after an earthquake has initiated but before strong motion begins at sites that may be damaged (See Research Studies 20, 21, 22, 23, and 24.)

8.2 Northern California Earthquake Management Center

In this section, we describe how the Northern California Earthquake Management Center fits within the CISN system. Figure 3.11 in Operational Section 2 illustrates the NCEMC as part of the 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 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, to have robust and reliable links for shipping waveform data and other information between the two processing systems.

Figure 3.29 provides more detail on the system operating at the NCEMC since mid-June, 2009. Now, 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 $M > 3.5$, 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 new 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 about 25 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 less than 30 seconds later, and other parameters, such as the peak ground acceleration and moment magnitude, follow within 1-4 minutes (Figure 3.30).

Earthquake information is now distributed to the web through EIDS and is available through the USGS Earthquake Notification Service (`http://sslearthquake.`

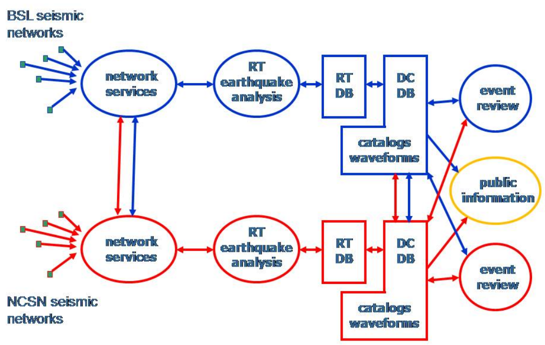

Figure 3.29: Details of the new Northern California processing system, which has been operational since mid-June, 2009. Network services processing, that is, production of picks, ground motion amplitudes, and other reduced information, occurs at both datacenters, and the information is exchanged. Complete earthquake information processing systems exist on both sides of the San Francisco Bay, and up-to-date information is exchanged by database replication.

`usgs.gov/ens`). We are working with the USGS in Golden, CO to implement exchange of earthquake information using a new transport mechanism, PDL. PDL allows larger packages of more complete information to pass from our analysis systems to the USGS as the National Earthquake Information Center in Golden and to other users. We are also working to develop readers and writers for QuakeML. Organizations with the need for more rapid earthquake information should use CISN Display (`http://www.cisn.org/software/cisndisplay.htm`). The *recenteqs* site has enjoyed enormous popularity since its introduction and provides a valuable resource for information which is useful not only in the seconds immediately after an earthquake, but in the following hours and days as well.

8.3 2011-2012 Activities

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 new Northern California system (Figure 3.31) has been modified to allow for local differences (such as very different forms of data acquisition and variability in network distribution). In addition, the BSL and the USGS want to minimize 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 new 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 made a number of suggestions on how to improve the performance of the magnitude module and has worked closely with Caltech and the USGS/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 next step in improving reliability and robustness is to implement ADA exchange with Southern California as well.

Moment Tensor Solutions with `tmts` and Finite Fault Analysis

The BSL continues to focus on the unique contributions that can be made from the broadband network, including moment tensor solutions and finite fault analysis. `tmts` 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 improved, web-based review interface has been operating in Northern California since July 2007. The automatically running version for real-time analysis was extensively tested and updated by Pete Lombard, and has been running since June 2009. Reporting rules now allow automatically produced solutions of high quality to be published to the web.

From July 2011 through June 2012, BSL analysts reviewed many earthquakes in Northern California and adjoining areas of magnitude 2.9 and higher. Reviewed mo-

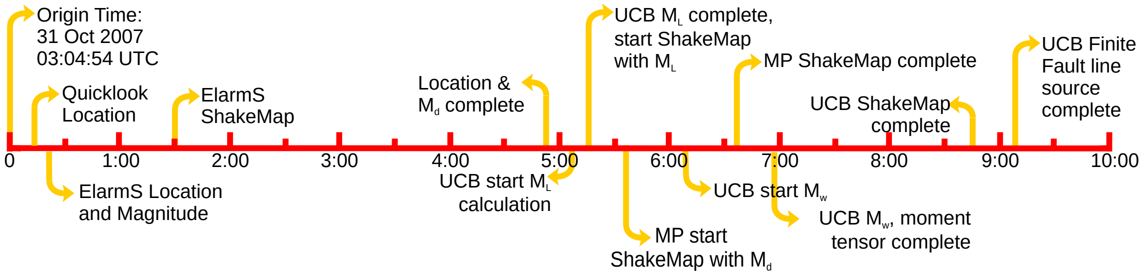

Figure 3.30: Illustration of the earthquake products timeline for the M_w 5.4 Alum Rock earthquake of October 30, 2007. Note that all processing was complete within 10 minutes of the origin time.

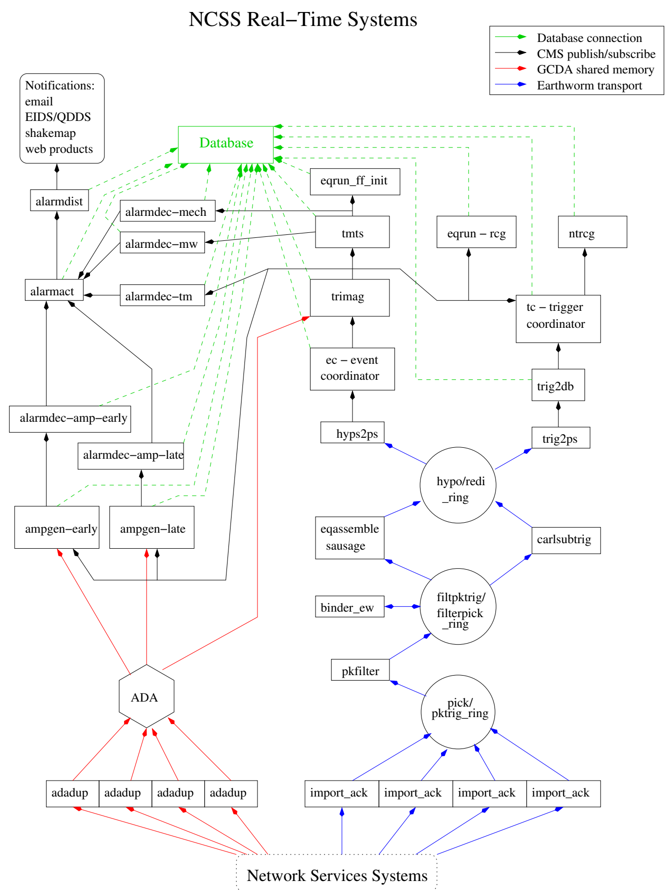

Figure 3.31: Schematic diagram of processing in the NCSS system. The design combines elements of the Earthworm, TriNet, and REDI systems

ment tensor solutions were obtained for 59 of these events (through 6/30/2012). Figure 3.32 and Table 3.17 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.

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. With the advent of the new code, we reviewed "old" events in the Geysers events from before 2007 with the new interface to produce and store deviatoric solutions for them in the database. In the next step, we will reanalyze events which exhibited anomalous radiation using the option for the full moment tensor (see Research Section 15). Some, but not all of these events will exhibit robust isotropic components.

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

Station Metadata, Reversals and `fpfit`

In a review of the fault plane solution for a recent event near the Geysers, we discovered that the orientation information for many of the seismic stations there was inconsistent. The fault plane solution program, `fpfit`, uses a file listing the stations with "reversed" polarity from the standard orientation. In the past, this file has been generated by hand and updated only occasionally. We reviewed the orientations of the borehole sensors contributing data to NCEMC operations, at Parkfield, in the San Francisco Bay Area and at the Geysers, using regional or teleseismic earthquakes. This information has been fed into the instrument response data. In a final step, we developed a procedure to compile the reversals file for `fpfit` from the database.

8.4 Routine Earthquake Analysis

In fiscal year 2010-2011, more than 27,000 earthquakes were detected and located by the automatic systems in Northern California. This compares with over 25,000 in 2009-2010, 21,500 in 2008-2009, 26,000 in 2007-2008, 23,000 in 2006-2007, 30,000 in 2005-2006, and 38,800 in 2004-2005. Many of the large number of events in 2004-2005 are aftershocks of the 2003 San Simeon and 2004 Parkfield earthquakes. Of the more than 27,000 events, about 126 had preliminary magnitudes of three or greater. Nine events had M_L or M_w greater than 4. The three largest events (on March 6, 2011, January 12, 2011 and March 1, 2011) had magnitudes close to 4.5. They were located offshore of Petrolia, CA, near San Juan Bautista, CA and near the Geysers, CA, respectively (see Table 3.17 for more details).

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.

8.5 Acknowledgements

Peggy Hellweg oversees our earthquake monitoring system and directs the routine analysis. Peter Lombard and Doug Neuhauser contribute to the development of software. Taka'aki Taira, Ingrid Johanson, Doug Dreger, Sierra Boyd, Holly Brown, Sanne Cottaar, Andrea Chiang, Shan Dou, Scott French, Aurelie Guilhem, Mong-Han Huang, Rob Porritt, Jennifer Taggart, Amanda Thomas, Tom Weldon, Kelly Wiseman, and Zhou (Allen) Zheng contribute to the routine analysis of moment tensors. Peggy Hellweg, Doug Neuhauser, and Taka'aki Taira 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.

8.6 References

Dreger, D., and B. Romanowicz, Source characteristics of events in the San Francisco Bay region, *USGS Open File Report 94-176*, 301-309, 1994.

Gee, L., J. Polet, R. Uhrhammer, and K. Hutton, Earthquake Magnitudes in California, *Seism. Res. Lett., 75(2)*, 272, 2004.

Gee, L., D. Neuhauser, D. Dreger, M. Pasyanos, R. Uhrhammer, and B. Romanowicz, The Rapid Earthquake Data Integration Project, *Handbook of Earthquake and Engineering Seismology*, IASPEI, 1261-1273, 2003a.

Gee, L., D. Dreger, G. Wurman, Y, Gung, B. Uhrhammer, and B. Romanowicz, A Decade of Regional Moment Tensor Analysis at UC Berkeley, *Eos Trans. AGU, 84(46)* , Fall Meet. Suppl., Abstract S52C-0148, 2003b.

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.

Romanowicz, B., D. Dreger, M. Pasyanos, and R. Uhrhammer, Monitoring of strain release in central and northern California using broadband data, *Geophys. Res. Lett., 20,* 1643-1646, 1993.

Location	Date	UTC Time	Lat.	Lon.	MT Depth	M_L	M_w	Mo	Str.	Dip	Rake
Tres Pinos, CA	7/6/2011	7:18:52	36.67	-121.29	8	3.73	3.8	6.20E+21	44	88	-14
Petrolia, CA	7/14/2011	13:18:44	40.32	-125.59	21	3.08	3.33	1.25E+21	97	82	162
Berkeley, CA	7/16/2011	10:51:26	37.86	-122.26	5	3.28	3.28	1.05E+21	145	87	-173
Tres Pinos, CA	7/18/2011	16:36:47	36.75	-121.34	8	3.12	3.17	7.12E+20	284	54	67
Petrolia, CA	8/5/2011	1:18:43	40.4	-124.96	8	3.09	3.55	2.59E+21	200	76	59
Alturas, CA	8/9/2011	16:28:08	41.52	-120.49	18	3.21	3.37	1.39E+21	313	83	-151
Trinidad, CA	8/14/2011	19:27:06	41.03	-125.17	18	3.7	4.1	1.79E+22	119	88	159
Anderson Springs, CA	8/17/2011	9:02:51	38.79	-122.75	5	3.43	3.67	4.03E+21	356	89	-179
San Leandro, CA	8/24/2011	6:36:54	37.74	-122.15	11	3.74	3.6	3.18E+21	69	89	-9
Mammoth Lakes, CA	8/24/2011	11:59:51	37.55	-118.87	8	4.34	4.23	2.71E+22	148	77	-133
San Leandro, CA	8/24/2011	16:57:44	37.75	-122.15	8	3.46	3.38	1.48E+21	140	80	-157
Pinnacles, CA	8/25/2011	18:17:35	36.58	-121.17	8	3.23	3.24	9.06E+20	41	85	-12
Pinnacles, CA	8/27/2011	7:18:21	36.58	-121.18	8	4.76	4.64	1.15E+23	135	82	-171
Pinnacles, CA	8/27/2011	7:22:00	36.6	-121.2	5	3.36	3.61	3.19E+21	38	76	-39
San Simeon, CA	9/13/2011	12:27:14	35.73	-121.11	5	3.69	3.56	2.71E+21	113	66	75
The Geysers, CA	9/17/2011	20:14:56	38.83	-122.8	3.5	3.02	3.38	1.47E+21	9	69	-131
San Leandro, CA	9/26/2011	3:08:10	37.75	-122.15	8	3.35	3.24	9.07E+20	54	89	-4
Angwin, CA	9/26/2011	9:01:23	38.6	-122.39	5	3.4	3.43	1.75E+21	147	66	153
Toms Place, CA	10/15/2011	11:42:30	37.91	-118.56	11	4.07	4.03	1.38E+22	203	51	-89
Berkeley, CA	10/20/2011	21:41:04	37.86	-122.25	8	4.1	3.95	1.01E+22	144	88	176
Berkeley, CA	10/21/2011	3:16:05	37.86	-122.26	8	4.13	3.84	7.20E+21	56	86	-9
Whitehawk, CA	10/27/2011	6:37:09	39.61	-120.47	14	5.18	4.73	1.55E+23	53	83	17
Berkeley, CA	10/27/2011	12:36:44	37.87	-122.26	11	3.8	3.62	3.39E+21	51	85	-9
Whitehawk, CA	10/30/2011	13:25:20	39.61	-120.48	14	4.05	3.8	6.32E+21	55	72	22
Kettleman City, CA	10/30/2011	13:26:44	35.94	-120.03	8	3.41	3.45	1.86E+21	322	65	111
Petrolia, CA	11/2/2011	7:21:06	40.41	-126.22	27	3.39	3.94	1.01E+22	182	89	14
Markleeville, CA	11/21/2011	9:39:04	38.54	-119.51	8	3.72	3.49	2.14E+21	203	50	-78
Petrolia, CA	12/8/2011	5:19:12	40.41	-125.59	14	3.52	4.02	1.35E+22	275	90	-168
Ferndale, CA	1/17/2012	9:55:01	40.53	-124.78	24	3.67	4.28	3.29E+22	124	83	-170
Clearlake, CA	1/24/2012	12:11:29	38.97	-122.69	11	3.39	3.8	6.20E+21	337	88	173
The Geysers, CA	1/30/2012	3:56:17	38.83	-122.8	5	2.9	3.31	1.14E+21	47	65	-60
Anderson Springs, CA	2/13/2012	4:47:13	38.79	-122.74	1.5	3.93	4.16	2.15E+22	67	89	-3
Weitchpec, CA	2/13/2012	21:07:03	41.14	-123.79	33	4.98	5.6	3.17E+24	215	48	-75
Crockett, CA	2/16/2012	2:09:14	38.08	-122.23	8	3.53	3.51	2.30E+21	144	90	-166
Crockett, CA	2/16/2012	17:13:21	38.08	-122.23	8	3.56	3.54	2.51E+21	55	82	-10
Petrolia, CA	2/25/2012	5:17:16	40.28	-124.31	30	3.6	4.28	3.24E+22	98	85	170
Weitchpec, CA	2/29/2012	5:00:33	41.14	-123.79	30	3.46	3.73	4.97E+21	345	75	-72
Pinnacles, CA	3/1/2012	16:31:09	36.64	-121.25	5	3.04	3.15	6.64E+20	45	89	-30
Pinnacles, CA	3/1/2012	17:15:34	36.64	-121.25	5	3.53	3.42	1.69E+21	139	83	156
El Cerrito, CA	3/5/2012	13:33:20	37.93	-122.31	8	4.24	3.99	1.19E+22	147	83	-170
Clearlake Oaks, CA	3/14/2012	6:30:21	39.02	-122.58	5	2.96	3.4	1.59E+21	68	76	-34
Cobb, CA	3/17/2012	23:21:23	38.83	-122.77	1.5	2.89	3.08	5.12E+20	166	52	-115
Petrolia, CA	3/19/2012	9:50:22	40.41	-124.59	21	3.24	3.61	3.19E+21	320	85	-168
Pinnacles, CA	4/6/2012	3:16:20	36.56	-121.12	5	3.82	3.69	4.21E+21	279	85	45
Aromas, CA	4/13/2012	22:18:54	36.89	-121.63	8	3.22	3.48	2.10E+21	314	78	-152
Trinidad, CA	4/17/2012	20:31:35	40.97	-124.42	21	3.51	4.15	2.10E+22	246	83	10
San Juan Bautista, CA	4/21/2012	15:19:10	36.78	-121.5	8	3.2	3.08	5.22E+20	44	87	-22
Petrolia, CA	4/27/2012	8:38:38	40.38	-124.99	8	3.5	3.83	6.82E+21	108	88	-172
The Geysers, CA	5/5/2012	9:23:23	38.8	-122.76	3.5	4.04	4.25	2.99E+22	143	87	-167
The Geysers, CA	5/5/2012	9:24:34	38.8	-122.78	1.5	0	3.34	1.29E+21	8	77	-161
The Geysers, CA	5/13/2012	12:38:52	38.79	-122.78	8	3.47	3.9	8.86E+21	169	82	164
Petrolia, CA	5/15/2012	10:19:33	40.39	-125.42	24	3.47	4.08	1.64E+22	93	81	168
Morgan Hill, CA	6/3/2012	17:31:37	37.26	-121.64	11	3.53	3.52	2.39E+21	235	84	-9
Trinidad, CA	6/10/2012	6:55:50	40.99	-124.83	24	3.4	3.55	2.65E+21	36	89	-7
Lee Vining, CA	6/11/2012	4:20:27	38.09	-119.14	8	3.36	3.16	6.92E+20	328	88	-164
Willow Creek, CA	6/13/2012	13:25:03	40.87	-123.47	18	3.26	3.4	1.55E+21	49	74	-64
Morgan Hill, CA	6/25/2012	8:13:41	37.26	-121.64	8	3.34	3.28	1.03E+21	326	89	-164
Willits, CA	6/25/2012	13:24:33	39.46	-123.32	8	3.24	3.47	1.99E+21	80	76	38
Ferndale, CA	6/30/2012	1:53:56	40.74	-125.15	14	3.67	3.97	1.14E+22	49	82	20

Table 3.17: Moment tensor solutions for significant events from July 1, 2011 through June 30, 2012 using a complete waveform fitting inversion. Epicentral information is from the UC Berkeley/USGS Northern California Earthquake Management Center. Moment is in dyne-cm and depth is in km.

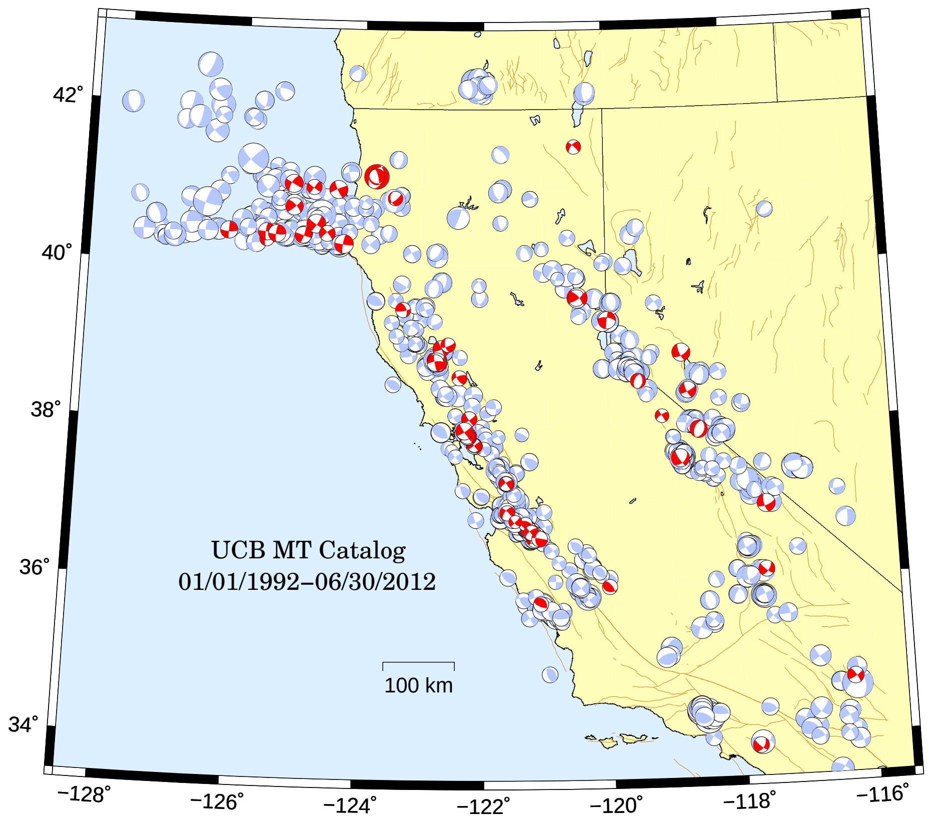

Figure 3.32: Map comparing reviewed moment tensor solutions determined by the BSL from past years (gray) with those from the fiscal year 2011-2012 (red/dark).

9 Outreach and Educational Activities

9.1 Introduction

BSL faculty, staff, and graduate students are involved in a wide variety of outreach activities, ranging from public lectures to tours of Hayward Fault geomorphology on campus. This year, of note was the BSL's response to the flood of media enquiries generated by the August 23 DC-area earthquake and by several mild to moderate earthquakes in the greater Berkeley area.

9.2 Highlights of 2011-2012

Responding to Media Enquiries

This year, the BSL's most far-reaching outreach activities were our interviews with local and national media. National news outlets contacted the BSL in response to the M 5.8 Mineral, VA earthquake that shook the Washington-DC area. Local earthquakes ranging in magnitude from 3.5 to 4.0 also generated a flurry of media requests. Faculty and researchers gave more than 30 interviews in 2011-2012, responding to over a dozen media enquiries for the DC-area quake alone.

In 2011-2012, Dr. Peggy Hellweg worked with KRON4 News to set up the USGS SWARM program for viewing seismic data. SWARM provides an alternative to the aging drum recorders currently filmed by news stations during an earthquake. (KRON and KPIX also continue to receive data feeds for their drum recorders from BSL station BKS via dedicated phone lines.)

Public Lectures

The Lawson Lecture is a free, public lecture hosted by the BSL every year in April. In this year's Lawson Lecture, Dr. Bill Ellsworth, from the US Geological Survey, gave a talk titled: "Earthquakes from the Top to the Bottom of the Magnitude Scale: Insights into Earthquake Physics from EarthScope." The Lawson Lectures are viewable as Flash video at `http://earthquakes.berkeley.edu/news/lawson_lecture`.

In October, 2011, Dr. Hellweg gave the monthly public Science@Cal lecture, entitled "Tectonic Timebombs: Earthquakes Near and Far." Also in conjunction with Science@Cal, as well as the San Francisco Arts Commission, Dr. Hellweg was featured on a panel of scientists and artists: "Vast and Undetectable: Artists and Scientists in Dialogue."

9.3 Ongoing Activities

During 2011-2012, many groups, ranging from elementary-school students to international guests, visited the BSL for talks, tours, and hands-on science experiences. BSL Director Richard Allen met with a Chinese delegation and spoke on Earthquake Early Warning and BSL operations, while Dr. Hellweg met with a delegation of Austrian provincial disaster management officials. Staff and graduate students conducted several talks and tours for school field trip groups and others. In addition, Drs. Johanson and Wiseman gave talks at the Lake Merritt Breakfast Club and a Bay Area middle school, respectively.

Recorded information on current earthquake activity is updated regularly on our information tape (510-642-2160).

Earthquake Research Affiliates Program

The UC Berkeley Earthquake Research Affiliates (ERA) Program links BSL researchers and their developments to those industry and public sector groups with an interest in BSL research. The purpose is to promote the use of new research and technology, and provide a forum for inviting optimal and essential users to participate in the development and testing of new technologies. The ERA program is designed to serve groups with an interest and need for rapid, robust and reliable earthquake information. This includes industrial groups with high-value equipment and products sensitive to earthquake ground shaking, public groups responsible for the safety of large cross-sections of society, and groups actively working to reduce the impacts of future earthquakes. More information on this public-private, industrial-academic community can be found on the ERA web pages (`http://earthquakes.berkeley.edu/ERA/`).

Cal Day - BSL Open House

The BSL once again opened its doors to visitors on UC Berkeley's *Cal Day*, the UC Berkeley open house for prospective students and community members. Visitors could jump up and down in front of a seismometer to make their own "earthquake," view current seismic data from our station BKS on a flatscreen monitor with the SWARM program, or learn about inertia and seismometers with a helium balloon tied to a radio-controlled car. Younger guests were offered their very own seismograms, while adults could pick up earthquake preparedness information provided by the BSL and the USGS. The BSL also participated in the Passport to Science@Cal program, helping children to fill up their "passports" with stamps and stickers from the *Cal Day* science exhibits they visited. Graduate student volunteers were on hand throughout the day to explain our exhibits and talk with visitors about UC Berkeley's role in earthquake monitoring.

Displays

A large flatscreen monitor featuring the USGS SWARM program is now mounted in the McCone Hall first floor lobby display case. Streaming real-time data from station BKS, the SWARM display allows students and visitors the opportunity to view up to 96 hours of seismic data.

The BSL provides local waveform feeds for helicorders at visitor centers associated with BDSN stations (CMB and MHC). Organizations such as LHS, KRON, and KPIX receive feeds from BKS via dedicated phone lines for display, while the USGS Menlo Park uses data from CMB for display in the lobby of the lecture hall.

BSL Web Pages

The BSL's main web pages describe our mission, introduce our research groups, provide information on our seminars and other special events (such as the Lawson Lecture), and point the public to sources of frequently sought-after earthquake-related information such as Alquist Priolo Zoning Act maps. The "seismic networks" web pages provide detailed information on each of our seismic stations, of interest to the research community. Our education and outreach web site (`http://earthquakes.berkeley.edu/outreach`) teaches the public about earthquakes and about Bay Area seismicity and hazards through Flash videos and FAQs while acting as a resource clearinghouse for teachers and those who wish to dig deeper. In addition, since September, 2008, the BSL has hosted its own blog, written by Horst Rademacher (`http://earthquakes.berkeley.edu/seismo.blog`).

9.4 Acknowledgements

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

Glossary of Common Acronyms

Table 3.18: Standard abbreviations used in this report.

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

Table 3.18: *continued*

Acronym	Definition
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
UNAVCO	University NAVSTAR Consortium
USGS/MP	United States Geological Survey/ Menlo Park
USNSN	United States National Seismic Network

Appendix I: Publications, Presentations, Awards, and Panels 2011-2012

Publications

Allen, R.M., Transforming Earthquake Detection? *Science, 335*, 297-298, doi: 10.1126/science.1214650, 2012.

Bodin, T., Sambridge, M., Rawlinson, N., & Arroucau, P., Transdimensional tomography with unknown data noise, *Geophys. J. Int., 189(3)*, 1536-1556, 2012.

Brossy, C.C., K.I. Kelson, C.B. Amos, J.N. Baldwin, B. Kozlowicz, D. Simpson, M.G. Ticci, A.T. Lutz, O. Kozaci, A. Streig, R. Turner, and R. Rose, Map of the late Quaternary active Kern Canyon and Breckenridge faults, Southern Sierra Nevada, California, *Geosphere, 8*, doi:10.1130/GES00663.1, 2012.

Cottaar S. and Buffett, B.A., Convection in the Earth's inner core, *Phys. Earth Planet. Int., 198-199*, 67-78, 2012.

Durand, S., J.P. Montagner, P. Roux, F. Brenguier and R.M. Nadeau, Passive monitoring of anisotropy change for the Parkfield 2004 earthquake, *Geophys. Res. Lett., 38*, L13303, doi:10.1029/2011GL047875, 2011.

Fisher, G.B., Amos, C.B., Bookhagen, B., Burbank, D.W., and Godard, V., Channel widths, landslides, faults, and beyond: The new world order of high spatial resolution Google Earth imagery in the study of earth surface processes, in Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and Virtual Visualizations in Geoscience Education and Research: Geological Society of America Special Paper 492, doi:10.1130/2012.2492(01), 2012.

Ford., S. R., W. R. Walter and D. S. Dreger, Event discrimination using regional moment tensors with teleseismic-P constraints, *Bull. Seism. Soc Am., 102*, 867-872, doi:10.1785/0120110227, 2012.

Guilhem, A., and D. S. Dreger, Rapid detection and characterization of large earthquakes using quasi-finite-source Green's functions in continuous seismic moment tensor inversion, *Geophys. Res. Lett., 38*, L13318, doi:10.1029/2011GL047550, 2011.

Kuyuk, H.S., E. Yildirim, E. Dogan, G. Horasan, An Unsupervised Learning Methodology: Application to discrimination of Seismic Event and Quarry Blasts in the Vicinity of Istanbul, *Natural Hazards and Earth Science, 11*, 93100, 2011.

Kuyuk, H.S., R.T. Kuyuk, E. Yildirim, Y. Sumer, Assessment of Near- And Far- Field Earthquake Ground Motion with Wavelet Transform, *Engineering Sciences, 6(1)*, 209-215, 2011.

H.S. Kuyuk, E. Yildirim, E. Dogan, G. Horasan, Application of k-means and Gaussian mixture model for classification of seismic activities in Istanbul, *Nonlinear Processes in Geophysics, 19(4)*, 401-419, 2012.

Lekic, V., French, S.W., and Fischer, K., Lithospheric Thinning Beneath Rifted Regions of Southern California, *Science, 334(6057)*, 783-787, DOI:10.1126/science.1208898, 2011.

Liu, K., Levander, A., Zhai, Y., Porritt, R. W., Allen, R. M., Asthenospheric flow and lithospheric evolution near the Mendocino Triple Junction, *Earth Planet. Sci. Lett., 323-324(1)*, 60-71, doi: 10.1016/j.epsl.2012.01.020, 2012.

Lutz, A., K.I. Kelson, C. Amos, D. Simpson, A. Jayko, and B. Kozlowicz, Seismic hazard, tectonics, and geomorphology of the southern Sierra Nevada range and southern Walker Lane belt, California, Friends of the Pleistocene Pacific Cell Annual Fieldtrip Guidebook, September 15 - 18, 2011, 158 p., 2011.

Malagnini, L., A. Akinci, K. Mayeda, I. Munafo, R.B. Herrmann, A. Mercuri, Characterization of earthquake-induced ground motion from the L'Aquila seismic sequence of 2009, Italy, *Geophys. J. Int., 184*, 325-337, 2011.

Obrebski, O., R.M. Allen, F. Zhang, J. Pan, Q. Wu, S.-H. Hung, Shear wave tomography of China using joint inversion of body and surface wave constraints, *J. Geophys. Res., 117*, B01311, doi:10.1029/2011JB008349, 2012.

Panning, M., A. Cao, A. Kim and B. Romanowicz, Non-linear 3D Born shear waveform tomography in southeast Asia, Geophys. J. Int., in press.

Pollitz, F., R. Bürgmann, and P. Banerjee, Geodetic Slip Model of the 2011 M9.0 Tohoku Earthquake, *Geophys. Res. Lett., 38(L00G08)*, doi:10.1029/2011GL048632, 2011.

Reddy, C. D., P. S. Sunil, R. Bürgmann, D. V. Chandrasekhar, and T. Kato, Postseismic relaxation due to Bhuj earthquake on January 26, 2001: possible mechanisms and processes, *Natural Hazards, 62*, doi: 10.1007/s11069-11012-10184-11067, 2012.

Romanowicz, B., and H., Yuan, On the interpretation of SKS splitting measurements in the presence of several layers of anisotropy, *Geophys. J. Int., 188*, 1129-1140, doi: 10.1111/j.1365-246X.2011.05301.x, 2012.

Ryder, I., R. Bürgmann, and F. Pollitz, Lower crustal relaxation beneath the Tibetan Plateau and Qaidam Basin following the 2001 Kokoxili earthquake, *Geophys. J. Int., 187(2)*, doi: 10.1111/j.1365-1246X.2011.05179.x, 2012.

Ryder, I., A. Rietbrock, K. Kelson, R. Bürgmann, M. Floyd, A. Socquet, C. Vigny, and D. Carrizo, Large extensional aftershocks in the continental forearc triggered by the 2010 Maule earthquake, Chile, *Geophys. J. Int.*, DOI: 10.1111/j.1365-1246X.2011.05321.x, 2012.

Shirzaei, M., A wavelet based multitemporal DInSAR algorithm for monitoring ground surface motion, *GRSL*, doi: 10.1109/LGRS.2012.2208935, 2012.

Shirzaei, M., R. Bürgmann, O. Oncken, T. R. Walter, P. Victor, and O. Ewiak (2012), Response of forearc crustal faults to the megathrust earthquake cycle: InSAR evidence from Mejillones Peninsula, Northern Chile, *Earth Planet. Sci. Lett.*, 333-334, doi:10.1016/j.epsl.2012.1004.1001.

Shirzaei, M., and R. Bürgmann, Topography correlated atmospheric delay correction in radar interferometry using wavelet transforms, *Geophys. Res. Lett., 39(L01305)*, doi:10.1029/2011GL049971, 2012.

Stehly, L., P. Cupillard and B. Romanowicz, Towards improving ambient noise tomography using simultaneously curvelet denoising filters and SEM simulation of ambient noise, C.R. *Geoscience, 343*, 591-599, 2011.

Thomas, A. M., R. Bürgmann, D. R. Shelly, N. M. Beeler, and M. L. Rudolph, Tidal triggering of low frequency earthquakes near Parkfield, CA: Implications for fault mechanics within the brittle-ductile transition, *J. Geophys. Res., 117(B05301)*, doi:10.1029/2011JB009036, 2012.

Uhrhammer, R.A., M. Hellweg, K. Hutton, P. Lombard, A.W. Walters, E. Hauksson and D. Oppenheimer: California Integrated Seismic Network (CISN) Local Magnitude Determination in California and Vicinity, *Bull. Seismol. Soc. Am., 101*, 2685-2693; doi:10.1785/0120100106, 2011.

Yoo, S-H, J. Rhie, H. Choi, K. Mayeda, Coda-derived source parameters of earthquakes and their scaling relationships in the Korean Peninsula, *Bull. Seism. Soc. Am., 101*, 2388-2398, 2011.

Zechar, J.D. and R.M. Nadeau, Predictability of repeating earthquakes near Parkfield, California, *Geophys. J. Int., 190*, 457-462, doi:10.1111/j.1365-246X.2012.05481.x, 2012.

Zhao, L., R.M. Allen, T. Zheng, R. Zhu, High-resolution body wave tomography models of the upper mantle beneath eastern China and the adjacent areas *Geochem. Geophys. GeoSys., 13*, Q06007, doi:10.1029/2012GC004119, 2012.

Presentations

Asia Oceania Geosciences Society, 2011, Taipei, Taiwan, August 8-12, 2011

Mong-Han Huang, Douglas Dreger, Seung Hoon Yoo, Roland Bürgmann, and Manabu Hashimoto, Joint Inversion of Seismic and Geodetic Data for the Source of the 4th March 2010 Mw 6.3 Jia-Shian, SW Taiwan, Earthquake.

Southern California Earthquake Center (SCEC) 2011 Annual Meeting, Palm Springs, CA, September 11-14, 2011

Nadeau, R.M., R.C. Turner, and R. Bürgmann, Slip Deficits, Release and Transients Along the Central SAF from Repeating Microearthquakes, Poster A-102.

EarthScope Institute on the Lithosphere-Asthenosphere Boundary, Portland, OR, September 19-21, 2011

Yuan, H., B. Romanowicz, D. Abt, H. Ford and K. Fischer, LAB and MLD in the NA Craton.

Association of Environmental and Engineering Geologists, 2011 Annual Meeting, Anchorage, AK, September 17-25, 2011

Cohen-Waeber, J., Bürgmann, R., Sitar, N., Landslide Risk Assessment (LSRA): GPS Instrumentation and Remote Sensing Study of Slope Movement In the Berkeley Hills, CA.

Seismological Society of Japan, Fall Meeting, Shizuoka, Japan, October 12-15, 2011

Taira, T., Detecting Stress-Induced Temporal Changes in Structures at Depth near Fault Zones from High-Frequency Seismic Coda Waves (invited).

Geothermal Resources Council Annual Meeting , San Diego, CA, October 23-26 2011

Dreger, D.S. Boyd, O.S., and Gritto, R., Deviatoric and full moment tensor analysis at The Geysers Geothermal Field.

Geoengineering Seminar, UC Berkeley, Berkeley, CA, November 30, 2011

Dreger, D. S., Seismic source-type identification and moment tensors of exotic events.

American Geophysical Union, 2011 Fall Meeting, San Francisco, CA, December 5-9, 2011

Allen, R.M., M. Boese, H. Brown, M. Caprio, G.B. Cua, M. Fischer, D.D. Given, E. Hauksson, T.H. Heaton, M. Hellweg, I. Henson, M. Luikis, P.J. Maechling, M.A. Meier, D.S. Neuhauser, D.H. Oppenheimer and K. Solanki, CISN ShakeAlert: Delivering test warnings for California earthquake, Abstract S52A-01.

Allen, R.M., A. Ziv. Application of real-time GPS to earthquake early warning, Abstract G33C-05.

Amos, C.B., J.R. Unruh, A. Lutz, G.B. Fisher, K.I. Kelson, D.H. Rood, and A.S. Jayko, Lithospheric control on spatial patterns of active faulting in the southeastern Sierra Nevada, California, Abstract T31B-2342.

Boyd, O.S., Dreger, D.S., Hellweg, M., Lombard, P., Ford, S.R., Taira, T., Taggart, J., and Weldon,T.J., Full moment tensor analysis at The Geysers Geothermal Field, Abstract S33A-2301.

Brown, H., Allen, R.M., Neuhauser, D., Henson, I., Hellweg, M., Lim, I., and the CISN-EEW project team, CISN ShakeAlert: ElarmS, Abstract S53A-2253.

Bürgmann, R., Thomas, R., Freed, A., Shelly, D., Strong Rocks and Weak Faults in the Lower Crust of California (invited), Abstract T21C-05.

Chiang, A., D.S. Dreger, S.R. Ford, and W.R. Walter, Free-Surface Vanishing Traction Effects on Shallow Sources, Abstract S43B-2233.

Chong, J., Yuan, H., French, S.W., Romanowicz, B.A., and Ni, S., Imaging 3D anisotropic upper mantle shear velocity structure of Southeast Asia using seismic waveform inversion, Abstract T33B-2409.

Cottaar S., and Romanowicz, B.A., Anisotropy across superplume boundaries, Abstract DI144A-02.

Cottaar S., and Romanowicz, B.A., Observations on the northern boundary of the Pacific Superplume and neighbouring ULVZ, Abstract DI132A-08.

Dziewonski, A.M., Lekic, V., Cottaar, S., Romanowicz, B.A., Topology of the mantle abyssal layer; superplumes big and small, Abstract DI132A-06.

French, S.W., Lekic, V., and Romanowicz, B.A., Toward global waveform tomography with the SEM: Improving upper-mantle images, Abstract S13C-02.

Guilhem, A., and Dreger, D. S., Rapid detection of great earthquakes using moment tensors: the example of the 2011 Tohoku-Oki earthquake, Abstract U51B-0005.

Hellweg, M, M. Vinci, The CISN-EEW project team, CISN ShakeAlert: Using early warnings for earthquakes in California, Abstract S53A-2254.

Johanson, I. R. Bürgmann, Characterizing Slow Slip Events on the Hayward Fault from Two Decades of SBAS-InSAR Data, Abstract S23B-2284.

Kelly, C.M., A. Rietbrock, D.R. Faulkner and R.M. Nadeau, Temporal Changes in Seismic Attenuation associated with the 2004 M6.0 Parkfield Event, Abstract S24A-01.

Kuyuk, H.S., R.M. Allen, M. Aktas, Earthquake Early Warning Systems; how many seconds do we really have?, Abstract S53A-2257.

Levander, A.; K. Liu; R.W. Porritt; R.M. Allen. The Seismic Structure of the Mantle Wedge under Cascade Volcanoes, T53A-2494.

Maceira, M., C.S. Larmat, C.A. Rowe, R.M. Allen, M.J. Obrebski, Validating Seismic Imaging Methods and 3D Seismic Velocity Models, Abstract S41A-2182.

Mayeda, K.M., Malagnini, L., Yoo, S., Apparent Stress of the M5.8 Mineral, Virginia Sequence and Comparison with Other Crustal Sequences using the Coda Ratio Methodology, Abstract S11B-2238.

Mayeda, K.M., Oth, A., Malagnini, L., Yoo, S., Walter, W.R., A Source Scaling Comparison for Selected Japanese Earthquake Sequences, Abstract S43C-2268.

Masson, Y., Romanowicz, B.A., and French, S.W., Superposition principle and waveform tomography. How well can we do?, Abstract S51D-03.

Mong-Han Huang, Roland Bürgmann, Manoochehr Shirzaei, Probing the Deep Rheology of Tibet: Constraints from the 2008 Mw 7.9 Wenchuan, China Earthquake, Abstract T23C-2411.

Neuhauser, D.S., I. Henson, R.M. Allen, CISN ShakeAlert: Decision Module Enhancements for Earthquake Alerts, Abstract S53A-2249.

Obrebski, M.J., R.M. Allen, F. Zhang, J. Pan, Q. Wu, F.F. Pollitz, S. Hung. Seismic tomography of the US and China using joint- inversion of body- and surface-wave constraints, Abstract S43D-03.

Porritt, R. W., Allen, R. M., Pollitz, F. F., Hung, S-H., Obrebski, M. J Lithosphere-asthenosphere structure beneath the United States from joint inversion of body waves, surface waves, and receiver functions, Abstract DI51A-2118.

Romanowicz, B.A., Lekic, V., Cottaar, S., Dziewonski, A.M., Seismological constraints on deep mantle processes, Abstract U44A-02.

Shirzaei, M.; Bürgmann, R., Spatiotemporal model of aseismic slip on the Hayward fault inferred from joint inversion of geodetic and seismic data time series, Abstract G22A-04.

Taira, T., Time-Lapse Monitoring for Detection of Transient Stress Changes in Geysers Geothermal Field, Abstract V53C-2630.

Thomas, A.M., N. M. Beeler, R. Bürgmann, and D. R. Shelly, The frequency dependence of friction in experiment, theory, and observations of low frequency earthquakes, Abstract S23B-2249.

Toomey, D.R.; R.M. Allen; J.A. Collins; R.P. Dziak; E.E. Hooft; D. Livelybrooks; J.J. McGuire; S.Y. Schwartz; M. Tolstoy; A.M. Trehu; W.S. Wilcock. Status of the Ocean Bottom Seismology Component of the Cascadia Initiative, Abstract T11C-08.

Turner R.C., Nadeau R.M., Bürgmann R., Aseismic Slip, Repeating Earthquakes and Fault Interaction in the Loma Prieta Aftershock Zone, Abstract S23B-2269 (OSPA Honorable Mention).

Wiseman, K., P. Banerjee, R. Bürgmann, K. E. Sieh,and D. Dreger, Joint Seismic and Geodetic Analysis of the 2009 Padang, Sumatra Intraslab Earthquake (invited), Abstract T54B-04.

Zhao, L., T. Zheng, R.M. Allen, Spatially varying upper mantle of eastern China caused by Pacific Plate subduction: constraints from body-wave tomography and SKS wave splitting measurements, Abstract S24B-08.

Zheng, Z. and Romanowicz, B., Small-scale Lateral Variations of S670S Characteristics at Okhotsk Sea Observed on the US Transportable Array, Abstract DI31B-2177.

Yoo, S., Dreger, D.S., Mayeda, K.M., Walter, W.R., Source Scaling and Ground Motion of the 2008 Wells, Nevada, earthquake sequence, Abstract S51B-2219.

Yuan, H., P. Cupillard, and B. A. Romanowicz, Refining upper mantle structure in the North American continent using Spectral Element method, Abstract S44A-05.

Yuan, H., French, S.W., Lekic, V., and Romanowicz, B., Global azimuthal anisotropy structure of the upper mantle, Abstract DI51C-03.

8th Annual Northern California Earthquake Hazards Workshop, USGS, Menlo Park, CA, January 24-25, 2012

Allen, R.M., H. M. Brown, M. Hellweg, D. Neuhauser, I. Henson, H.S. Kuyuk, CISN Earthquake Early Warning.

Johanson, I., R. Bürgmann, The BARD Continuous GPS Network: Monitoring Earthquake Hazards in Northern California and the San Francisco Bay Area.

Johanson, I., R. Bürgmann, BAVU3$\beta\epsilon\tau\alpha$ The BARD Continuous GPS Network: Monitoring Earthquake Hazards in Northern California and the San Francisco Bay Area.

Shirzaei, M., T. Taira, I. Johanson, R. Bürgmann, Transient Slip on the Hayward Fault from SBAS-InSAR, GPS and Seismicity Data.

Turner R.C., Nadeau R.M., Bürgmann R., Aseismic Slip, Repeating Earthquakes and Fault Interaction in the Loma Prieta Aftershock Zone.

Big Data at Berkeley, Berkeley EECS Annual Research Symposium, Berkeley, CA, February 23, 2012

Kong, Q., Allen, R.M., Bray, J., Bayen, A., droidShake: Using smartphones to provide earthquake warnings.

2012 UNAVCO Science Workshop, Boulder, CO, February 28- March 1, 2012

Johanson, I., Real-time Data Processing for Retrieving Earthquake Parameters from the BARD Network.

T. Taira, K. Hodgkinson, O. Fox, and D. Mencin, Measurements of PBO Borehole Seismometer Orientations.

International Symposium on Statistical modeling and Real-time Probability Forecasting for Earthquakes, Institute of Statistical Mathematics, Tokyo, Japan, March 11-14, 2012

Nomura, S., Y. Ogata and R.M. Nadeau, Space-Time Models of Repeating Earthquakes in Parkfield Segment.

European Geophysical Union, Vienna, Austria, April 22-27, 2012.

Levander, A., K. Liu, R.W. Porritt, R.M. Allen, The Seismic Structure of the Mantle Wedge under Cascade Volcanoes.

2012 Seismological Society of America Annual Meeting, San Diego, CA, April 17-19, 2012

Allen, R.M., I. Johanson, S. Colombelli, A. Ziv, Applications of real-time GPS to earthquake early warning.

Beeler, N.M., A. M. Thomas, R. Bürgmann, and D. R. Shelly, Modulation of tectonic tremor by the tides: physical models descended from Leon Knopoff with application to the deep San Andreas.

Dreger, D. S., A. Guilhem, O. S. Boyd, A. Chiang, and M Hellweg, Seismic source studies at the Berkeley Seismological Laboratory, *Seism. Res. Lett., 83(2), 383*, 2012.

Guilhem, A., and Nadeau, R. M., Episodic Tremor as Slow-slip events (SSE) at Parkfield, CA, *Seism. Res. Lett., 83(2)*, 2012.

Hellweg, M., R.M. Allen, H. M. Brown, I. Henson, Q. Kong, H.S. Kuyuk, D. Neuhauser, Developments in Earthquake Early Warning at UCB: CISN ShakeAlert.

Maceira, M., Larmat, C., Allen, R. M., Porritt, R., Rowe, C., Obrebski, M., 3D Seismic models and Finite-Frequency vs. Ray Theoretical approaches.

Porritt, R. W., Allen, R. M., Poolitz, F. F., Hung S-H., Obrebski, M. J., Lithosphere-Asthenosphere structure beneath the United States from joint inversion of body waves and surface waves.

Taira T., Investigating Interactions of Creeping Segments with Adjacent Earthquake Rupture Zones in the Mendocino Triple Junction Region.

GSA Rocky Mountain Section 64th Annual Meeting, Albuquerque, NM, May 9-11, 2012

Porritt, R. W., Allen, R. M, Pollitz, F. F., The Rocky Mountains in the context of the North American continent from jointly inverted body and surface wave tomography.

3rd QUEST workshop, Tatranska Lomnica, Slovakia, May 20-26, 2012

Cottaar S., and Romanowicz, B.A., A large ULVZ beneath Hawaii from S diffracted waveform modeling.

Romanowicz, B.A., Full waveform modeling of the earth's mantle at the global scale: from normal modes to SEM (invited).

Global challenges for seismological data analysis, 38th Workshop of the International School of Geophysics, Erice, Sicily, 25-30 May, 2012

Kong, Q., Allen, R.M., Bray, J., Bayen, A., myShake: Using smartphones to detect earthquakes.

Annual IRIS workshop, Boise, ID, June 13-15, 2012

Allen, R.M., When N is not enough: Engaging citizen scientists to expand geophysical networks (invited).

Guilhem, A., and Nadeau, R. M., Nonvolcanic Tremors and Deep Slow Slip Events in Central California.

Asia Oceania Geosciences Society - American Geophysical Union Western Pacific Geophysics Meeting (AOGS - AGU (WPGM)) Joint Assembly, Resorts World Convention Centre, Singapore, August 13-17, 2012

Chen K.H., R. Bürgmann and R.M. Nadeau, Do Earthquakes Talk to Each Other? Triggering and Interaction of Repeating Sequences at Parkfield, Abstract SE76-A001.

Speaking Engagements

Allen, R.M., Using Real Time GPS to Deliver Earthquake Early Warning in California, Civil GPS Service Interface Committee, Sacramento, CA, August 2011.

Allen, R.M., NSF's Amphibious Array, GeoPrisms Alaska Implementation Planning Meeting, Portland, Oregon, September 2011.

Allen, R.M., Delivering earthquake warnings to California, UC Berkeley Science Talks, San Francisco, California, September 2011.

Allen, R.M., Delivering Earthquake Early Warning to California, University of California Town and Gown Meeting, Berkeley, California, October 2011.

Allen, R.M., NSF's Amphibious Array, Earthscope Steering Committee Meeting, Phoenix, Arizona, October 2011.

Allen, R.M., Delivering Earthquake Early Warning to California, Northern California Geological Society, Orinda, California, October 2011.

Allen, R.M., M.J. Obrebski, R. Porritt, C. Eakin, F. Pollitz, S. Hung, Mantle upwelling and lithospheric destruction beneath western North America, Dept. Earth and Planetary Sciences, Washington University in St Louis, Missouri, November 2011.

Allen, R.M., Scientific briefing for Jacob Appelsmith, Senior Advisor to Governor Jerry Brown, State of California, December 2011.

Allen, R.M., Scientific briefing for Federal Executive Board (with representatives for all federal agencies with a presence in the San Francisco Bay Area), March 2012.

Allen, R.M., Scientific briefing for City of San Francisco, San Francisco, CA, April 2012.

Allen, R.M. Reaching beyond the Ivory Tower: Reducing earthquake hazard while driving scientific discovery. Princeton University, New Jersey, April 2012.

Allen, R.M., Scientific briefing for Advisors for Senators Barbara Boxer and Dian Feinstein, and Representatives John Garamendi, Jerry McNerney and Jackie Speier, Washington DC, May 2012.

Allen, R.M., Scientific briefing for California Emergency Management Agency, May 2012.

Allen, R.M., When N is not enough: Beyond traditional seismic networks. Global challenges for seismological data analysis, Fondazione Ettore Majorana, Erice, Italy, May 2012.

Allen, R.M., California's dual-use geophysical networks: Increased science, reduced risk. Global challenges for seismological data analysis, Fondazione Ettore Majorana, Erice, Italy, May 2012.

Allen, R.M., Scientific briefing for California Council on Science and Technology, June 2012

Amos, C.B., Active faulting and regional deformation of the southern Sierra Nevada block, San Jose State University, San Jose, CA, November 7, 2011.

Amos, C.B., Spatial and temporal patterns of faulting and active deformation of the Sierra Nevada, CA, California State University Bakersfield, Bakersfield, CA, February 8, 2012.

Amos, C.B., What can ancient rivers tell us about active faults?, Western Washington University, Bellingham, WA, April 5, 2012.

Amos, C.B., Spatial and temporal patterns of faulting and active deformation of the Sierra Nevada, CA, Berkeley Seismological Laboratory, Berkeley, CA, April 24, 2012.

Bürgmann, R., Lithosphere and Asthenosphere Rheology from Post-loading Deformation, EarthScope Institute on Lithosphere-Asthenosphere Boundary, Portland, OR, September 19, 2011.

Bürgmann, R., The Role of Fluids in the Rheology of Rocks and Fault Zones in the Lower Crust and Upper Mantle, Geofluids Symposium: Dynamics and Evolution of the Earth's Interior, Misasa, Japan, March 18, 2012.

Cottaar S., Earthquakes and Seismology, for the Stamford School, UK, at UC Berkeley, Berkeley Seismological Laboratory, July 18, 2011.

Cottaar S., Seismic anisotropy and superplume boundaries in the D" region, Bullard Laboratories Wednesday Colloquia, Cambridge, UK, September 2011.

Dreger, D. S., Seismic source-type identification and moment tensors of exotic events, Earth Science Seminar, Scripps, University of California, San Diego, CA, April 16, 2012.

Guilhem, A., The power of near (almost) realtime moment tensors, Exit Seminar, Berkeley Seismological Laboratory, UC Berkeley, November 20, 2011.

Guilhem, A., Analysis of unusual earthquake and tremor seismicity at the Mendocino Triple Junction and Parkfield, California, PhD Defense, Institut de Physique du Globe, Paris, March 28, 2012.

Hellweg, M., Tectonic Timebombs: Earthquakes Near and Far, Science@Cal Lecture Series, UC Berkeley, Berkeley, CA, October 15, 2011.

Hellweg, M., Vast and Undetectable Panel Discussion: Visual Languages of Art and Science, San Francisco Arts Commission Gallery, San Francisco, CA, March 21, 2012.

Johanson, I., Transient Slip on the Hayward Fault from SBAS-InSAR, FRINGE 2011, Frascati, Italy, September 19-23, 2011.

Johanson, I., Earthquakes on the Hayward Fault, Lake Merritt Breakfast Club, Oakland, CA, January 12, 2012.

Johanson, I., Earthquake Early Warning and Cascadia, GeoPRISMS/EarthScope Planning Workshop for the Cascadia Primary Site, Portland, OR, April 5-6, 2012.

Nadeau R.M., Repeating Earthquake Recurrence Intervals: Magnitude and Time-Dependence, International Symposium on Statistical Modeling and Real-time Probability Forecasting for Earthquakes, The Institute of Statistical Mathematics, Tokyo, Japan, March 11-14, 2012.

Nadeau R.M., Repeating Earthquakes: Some Physical Considerations, National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan, March 16, 2012.

Romanowicz, B., Lateral variations in seismic structure and anisotropy in the lowermost mantle, UCL-IPGP Workshop on high pressure Physics, Paris, September 2011.

Romanowicz, B., Stratification in the lithosphere in archean cratons: evidence from seismic waveform tomography, University College London, London, UK, November 1, 2011.

Romanowicz, B., Stratification in the lithosphere in archean cratons: evidence from seismic waveform tomography, Institut de Physique du Globe, Paris, France, November 10, 2011.

Romanowicz, B., Global seismic tomography in the age of numerical wavefield computations, Department of Statistics, UC Berkeley, February 22, 2012

Romanowicz, B., Global seismic tomography in the age of numerical wavefield computations, USGS Menlo Park, Menlo Park, CA, May 9, 2012.

Taira, T., Seismic Constraints on Fault-Zone Strength and Rheology at Seismogenic Depth on the San Andreas Fault, Parkfield, National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan, October 17, 2011.

Taira, T., Seismic Constraints on Fault-Zone Rheology at Depth from Characteristically Repeating Earthquakes at Parkfield, California, Kyoto University, Kyoto, Japan, October 18, 2011.

Taira, T., Seismic Constraints on Fault-Zone Rheology at Depth from Characteristically Repeating Earthquakes at Parkfield, California, California State University Northridge, Department of Geological Sciences Colloquia, Northridge, CA, November 1, 2011.

Taira, T., Seismic Constraints on Fault-Zone Rheology at Depth from Characteristically Repeating Earthquakes at Parkfield, California, Caltech Dix Seismological Laboratory seminar, Pasadena, CA, November 4, 2011.

Wiseman K., The far reach of megathrust earthquakes: evolution of stress, deformation, and seismicity following the 2004 Sumatra-Andaman earthquake, UC Berkeley, Berkeley Seismological Laboratory Seminar, May 1, 2011.

Wiseman, K., My life as a geophysicist, Raymond J. Fisher Middle School, Los Gatos, CA, June 1, 2011.

Wiseman K., The far reach of megathrust earthquakes: evolution of stress, deformation, and seismicity following the 2004 Sumatra-Andaman earthquake, USGS Earthquake Science Center, Menlo Park, CA, June 13, 2011.

Yuan, H., and B. A. Romanowicz, Exploring the North American Upper Mantle Using EarthScope Data, EarthScope Transportable Array Working Group Webinar, January 11, 2012.

Yuan, H. and B. A. Romanowicz, Probing the North American Continent Using Seismic Anisotropy, Shell Colloquium Series, Spring 2012, ConocoPhillips School of Geology & Geophysics, The University of Oklahoma, Norman, OK, January 26, 2012.

Awards

Barbara Romanowicz

2012 Harry F. Reid Medal, Seismological Society of America

Panels and Professional Service

Richard M. Allen

Member, Cascadia Initiative Expedition Team Chair, International Earthquake Early Warning Advisory Committee, Geological Institute of Israel
Member, Scientific Advisory Board, European Union Framework 6 Project: Strategies and tools for Real Time EArthquake RisK ReducTion (REAKT)
Chair, Amphibious Array Steering Committee (for the NSF Cascadia Initiative)
Chair, IRIS PASSCAL Standing Committee
Convener, Special sessions: “The origin of intraplate volcanism: hotspots, non-hotspots, and large igneous provinces” and ”Earthquake Early Warning Capabilities and Delivery Around the World”. AGU December 2011.

Roland Bürgmann

Associate Editor, Bulletin of the Seismological Society of America
Editorial Advisory Board, Eos
Editorial Board, Earth and Planetary Science Letters
Member, EarthScope PBO Advisory Committee
Co-chair, EarthScope Thematic Working Group on Crustal Strain and Deformation
Member, National Earthquake Prediction Evaluation Council (NEPEC)

Douglas S. Dreger

Cosmos Board of Directors
Four day short course on Moment Tensors in Quito, Ecuador (Pan-American Advanced Studies Institute on New Frontiers in Seismological Research: Sustainable Networks, Earthquake Source Parameters, and Earth Structure, July 11-24, 2011)

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 Comprehensive Catalog Advisory Committee
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

Douglas S. Neuhauser

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

Barbara Romanowicz

Member, International Evaluation Committee, School of Earth Sciences, ETH Zurich
Member, International Review Committee, Earth Observatory of Singapore
GEOSCOPE Scientific Adv. Committee, Paris
Recruitment committee, Geophysics faculty position, École Normale Supérieure, Paris
Scientific Advisory Committee, Dept of Geology, École Normale Supérieure, Paris
Member, COMPRES advisory committee

Taka'aki Taira

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 2011-2012

WALTER MOONEY
USGS
"Field assessments and Seismology of the M=8.8 Chile and M=9.0 Japan earthquakes"
Tuesday, August 30, 2011

ISABELLE RYDER
University of Liverpool
"Stressful times following the 2010 Maule earthquake, Chile"
Tuesday, September 6, 2011

No seminar
Tuesday, September 13, 2011

No seminar
Tuesday, September 20, 2011

MANOOCHEHR SHIRZAEI
UC Berkeley
"Spatiotemporal deformation field monitoring and modeling using advanced InSAR time series and time-dependent modeling"
Tuesday, September 27, 2011

No seminar
Tuesday, October 4, 2011

MARGARET SEGOU
USGS Menlo Park
"Post seismic stress evolution in strike slip faults along plate boundaries Comparing Northern California with Western Greece"
Tuesday, October 11, 2011

CHRISTINA MORENCY
Lawrence Livermore National Laboratory
"Seismic imaging based on spectral-element and adjoint methods: application to geothermal reservoir management"
Tuesday, October 18, 2011

SEUNG HOON YOO
UC Berkeley
"Earthquake Source Scaling and Ground Motion: Comparison for selected Japanese and west US earthquake sequences"
Tuesday, October 25, 2011

ERIC FIELDING
JPL
"Complex Fault Rupture of the 2010 El Mayor-Cucapah Earthquake in Baja California"
Tuesday, November 1, 2011

KEITH KNUDSEN
USGS Menlo Park
"Geomorphic and Geologic Evaluation of Liquefaction Case Histories: Toward Rapid Hazard Mapping"
Tuesday, November 8, 2011

ROSS STEIN
USGS Menlo Park
"What triggers most earthquakes? (The answer's in the shadows)"
Tuesday, November 15, 2011

AURELIE GUILHEM
UC Berkeley
"The power of near-realtime moment tensors: application for small to tsunamigenic earthquakes"
Tuesday, November 22, 2011

GILEAD WURMAN
Seismic Warning Systems
"Benefits and Challenges of Designing an Earthquake Warning System from the Ground Up"
Tuesday, November 29, 2011

CHIN-WU CHEN
Carnegie Institution of Washington
"Upper mantle structure beneath the High Lava Plains, eastern Oregon, imaged by scattered wavefield"
Tuesday, December 13, 2011

SERDAR KUYUK
UC Berkeley
"Forward Forecasting of Ground Motion for Earthquake Early Warning Using Artificial Neural Network and Its Advanced Engineering Applications"
Tuesday, January 17, 2012

No seminar
Tuesday, January 24, 2012

EMILY MONTGOMERY-BROWN
University of Wisconsin
"Kilauea Slow Slip Events and the Hunt for Tectonic Tremor"
Tuesday, January 31, 2012

MAURIZIO BATTAGLIA
University of Rome I "La Sapienza"
"Modeling Unrest at Mount St Helens"
Tuesday, February 7, 2012

VICTOR TSAI
Caltech
"Quantifying the Seismic Signature of Rivers and Sea Ice"
Tuesday, February 14, 2012

BRAD AAGAARD
U.S. Geological Survey
"Probabilistic Estimates of Surface Coseismic Slip and Afterslip for Hayward Fault Earthquakes"
Tuesday, February 21, 2012

ARMEN DER KIUREGHIAN
Department of Civil & Environmental Engineering, UC Berkeley
"Bayesian Network for Post-Earthquake Risk Assessment and Decision"
Tuesday, February 28, 2012

RONNI GRAPENTHIN
University of Alaska Fairbanks
"Volcano Geodesy on Gliding Timescales: Sources, Plumes, and Precursory Signals"
Tuesday, March 6, 2012

ANDY FREED
Purdue University
"Using earthquakes as large rock squeezing experiments"
Tuesday, March 13, 2012

LINGSEN MENG
Caltech
"The Broad Spectrum of Earthquake Ruptures Inferred from High Resolution Array Back-Projections"
Tuesday, March 20. 2012

No seminar
Tuesday, March 27, 2012

SARAH MINSON
U.S. Geological Survey
"Bayesian Earthquake Source Modeling"
Tuesday, April 3, 2012

JONATHAN AJO-FRANKLIN
Lawrence Berkeley National Laboratory
"Using Continuous Active Source Seismic Monitoring (CASSM) for Mapping Injected CO2 and Evolving Hydraulic Fractures"
Tuesday, April 10, 2012

No seminar
Tuesday, April 17, 2012

COLIN AMOS
UC Berkeley
"Spatial and Temporal Patterns of Active Faulting and Deformation of the Southeastern Sierra Nevada, CA"
Tuesday, April 24, 2012

BILL ELLSWORTH
USGS
"Earthquakes from the Top to the Bottom of the Magnitude Scale: Insights into Earthquake Physics from EarthScope"
2012 Lawson Lecture
Wednesday, April 25, 2012

KELLY WISEMAN
Berkeley Seismological Lab.
"The Far Reach of Megathrust Earthquakes: Evolution of Stress, Deformation and Seismicity following the 2004 Sumatra Earthquake"
Tuesday, May 1, 2012

Berkeley Seismological Laboratory
Organizational Chart
2011 -2012