USGS Award Number G09AC00487

Final Technical Report

Upgrading the Broadband and Borehole Seismic Networks Operated by the Berkeley Seismological Laboratory at the University of California, Berkeley

Award Term:
September 15, 2009 – August 31, 2011

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Abstract: In Northern California, the University of California Berkeley Seismological Laboratory (BSL) and the USGS Menlo Park (MP) collaborate closely to provide timely and reliable earthquake information to the federal, state, and local governments, to public and private agencies, to researchers nation- and worldwide and to the general public. For this purpose, the BSL operates seismic instrumentation in Northern California. Broadband and/or strong motion sensors are now installed at 35 sites. At 28 sites three-component geophones and/or accelerometers are deployed in boreholes. The equipment at these sites was installed over the past twenty years, with a large proportion being older than 5 years. In this project, we upgraded out-of-date and aging equipment data loggers to bring the seismic networks operated by the Berkeley Seismological Laboratory up to state-of-the art. Upgrades were made at 25 sites of the Berkeley Digital Seismic Network (BDSN), 13 sites of the Parkfield, CA, borehole High Resolution Seismic Network (HRSN), and 9 sites of the borehole Northern Hayward Fault Network (NHFN). The goal of these activities is to enhance and improve earthquake reporting in northern California, and to maintain the collection of high quality data for scientific purposes.

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1. Introduction

In northern California, the Berkeley Seismological Laboratory (BSL) and the U.S. Geological Survey (USGS) Menlo Park collaborate closely to provide timely and reliable earthquake information to federal, state, and local governments, to public and private agencies, to researchers nation- and worldwide and to the general public. This joint management of earthquake related data comprises two closely related activities: (1) a joint real-time earthquake notification system, the Northern California Earthquake Management Center (NCEMC) and 2) an on-line archive for digital data pertaining to earthquakes, the Northern California Earthquake Data Center (NCEDC). A Memorandum of Agreement between the USGS/MP and BSL governs this cooperative effort (http://seismo.berkeley.edu/bsl-usgs-mou.pdf).

The joint earthquake notification system of the NCEMC provides enhanced earthquake monitoring by building on the strengths of the Northern California Seismic Network (NCSN), operated by the USGS Menlo Park, and the Berkeley Digital Seismic Network (BDSN, Figure 1), operated by the UC Berkeley Seismological Laboratory, and by taking advantage of combined software development efforts. The BSL and USGS began collaborating on the joint notification system for northern and central California in 1996 [*Gee et al.*, 1996]. Today, the joint BSL /USGS system forms the NCEMC of the California Integrated Seismic Network (CISN), which is the California "region" of the ANSS. Since June 2009, the NCEMC uses the ANSS Software for earthquake reporting. By providing real-time information on earthquakes in northern California, including locations, magnitudes, moment tensors, finite fault models and ShakeMaps, this activity provides key products relevant to the goals of the ANSS and the National Earthquake Hazards Reduction Program (NEHRP). The BSL is currently also participating in, and contributing data to the development and testing of earthquake early warning algorithms in California. Telemetry delays introduced by data loggers can be a major stumbling block toward producing earthquake information very rapidly.

Earthquake processing at the BSL and data archiving activities of the NCEMC are performed through the Northern California Earthquake Data Center (NCEDC). The NCEDC was established in 1991 as a joint project of the Berkeley Seismographic Station (now the BSL) and the USGS Menlo Park to serve as an "on-line" archive for parametric and digital waveform data from geophysical networks in northern and central California. Such data are a cornerstone of research towards the goals of the National Earthquake Hazards Reduction Program (NEHRP). The NCEDC is located at U.C. Berkeley, operated jointly with the USGS, and has been accessible to the user community through the Internet since mid-1992 [*Bogaert* et al., 1992; *Romanowicz* et al., 1994]. A philosophy of the NCEDC from the very beginning has been to archive *continuous* data. This has paid off with the recent discoveries or rediscoveries of useful signals in broadband data (microseismic noise, earth's hum, e.g. *Rhie and Romanowicz*, 2004], as well as the development of methods that use background noise to investigate crustal structure [e.g. *Shapiro and Campillo*., 2004]. Recently, the discovery of non-earthquake tremors in subduction zones [*Obara*, 2002; *Rogers and Dragert*, 2003] and on the San Andreas Fault [*Nadeau and Dolenc*, 2004], combined with inexpensive on-line data storage has allowed us to extend the continuous recording to data from short period and borehole stations and to data recorded at higher sampling rates.

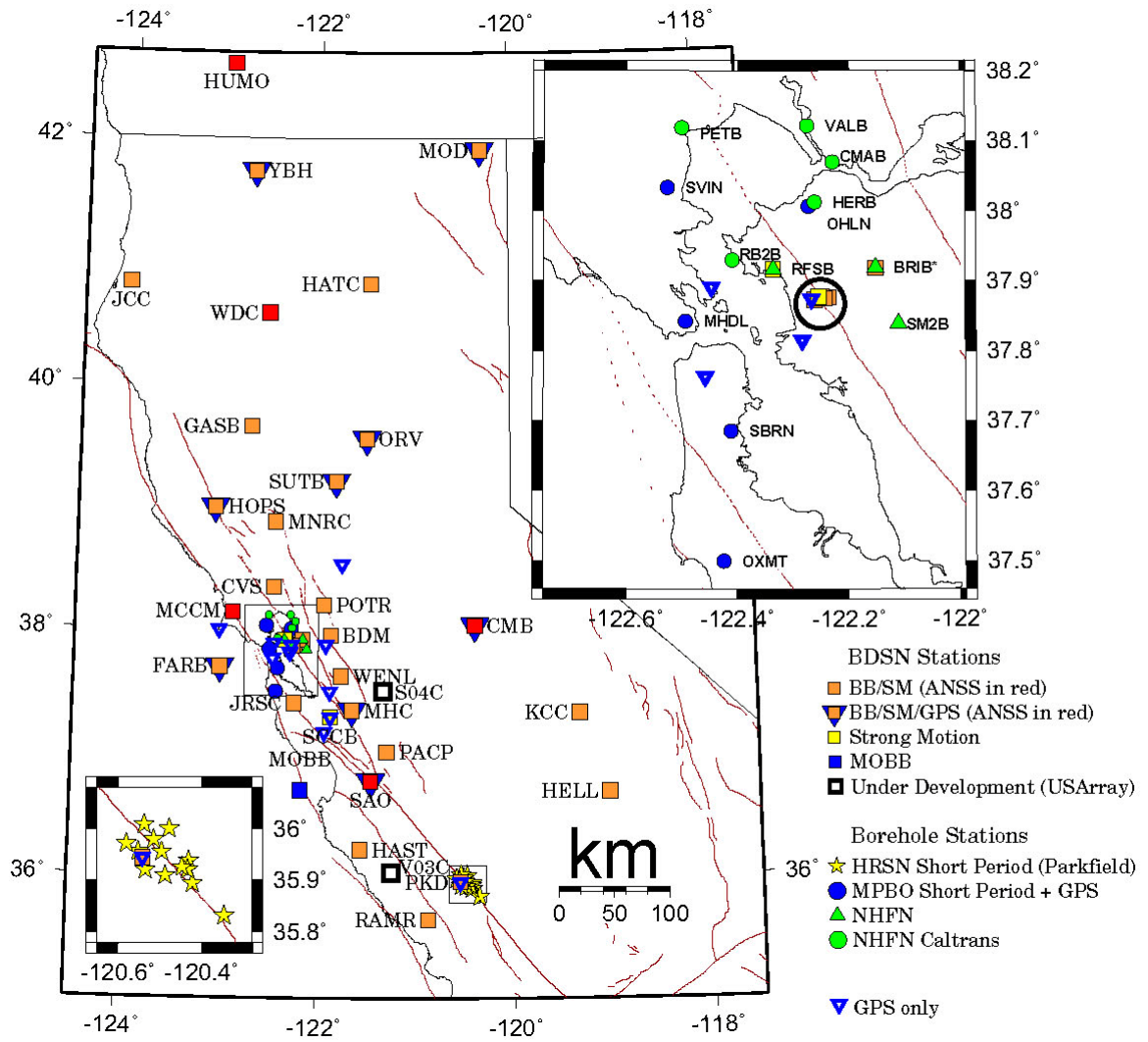

Figure 1: Map illustrating the BSL networks in Northern and Central California. UCGS, CalEMA and Caltrans contribute to operating these stations. ANSS backbone stations are shown in red. In the inset map, the shown stations in the circle include BRK, BKS, CMSB, VAK, BL88, and BL67. * Station BRIB is also a GPS and mPBO site. Abbreviations: BB/SM - Broadband/Strong Motion; BB/SM/GPS - Broadband/Strong Motion/GPS.
Stations NOT intended for upgrade as part of this project are: BL67, BL88, CVS, HAST, HATC, HELL, RAMR, SUTB, VAK, CMAB, HERB, PETB, RB2B, VALB and WO2B. We received GFE equipment to replace data loggers at KCC, CMSB and RMNB, but have not been able to deploy it yet (see text).

In addition to the BDSN, which is equipped with seismic broadband and strong motion instrumentation, the BSL operates two geographically more focused, borehole seismic networks, the High Resolution Seismic Network (HRSN) on the San Andreas Fault near Parkfield (CA) (box on lower left in Figure 1) and the Northern Hayward Fault Network (NHFN) along the Hayward Fault in the San Francisco bay area (Figure 1). The operations and maintenance of the 13 HRSN stations and 9 stations of the NHFN, which include 5 stations originally deployed as part of the "mini- PBO" network, are supported by ANSS cooperative agreement. The NHFN is the Berkeley component of a larger borehole network along the Hayward Fault, where the remaining sites on the southern portion of the fault (SHFN) are operated by the USGS/Menlo Park. Additional Bay Area borehole sites are operated with support

from Caltrans. The borehole networks are now fully integrated into California real-time seismic monitoring through the Northern California Seismic System (NCSS) processing stream and play dual roles by contributing both to response applications and the collection of basic data for long-term hazards mitigation, and by complementing surface networks with coverage of high-gain, high-sample-rate (up-to 500 sps), low-noise borehole recordings of very low amplitude seismic signals for fundamental research on earthquake related problems.

Though the role of the borehole networks for response applications and basic data collection is an important one, the special properties of the borehole data make these networks additionally valuable though their unique ability to contribute to cutting edge research on earthquake source and fault zone questions [*Nadeau et al.*, 2008]. The unprecedented resolution provided by the borehole network data has driven some of our research, and stimulated that of many colleagues for over a decade. It contributes to NEHRP by providing the basis for some of the research supported by NEHRP at the BSL, and at other organizations, as well as complementary research by investigators from other nations. Recent examples of such research include: (1) correlation analysis of ambient seismic noise to monitor fault zone velocity changes [*Brenguier et al*., 2008]; (2) analysis of non-volcanic tremor activity to explore very deep (sub-seismogenic) fault zone structure, rheology and processes such as stress-transfer and deformation [*Shelly et al.*, 2009; *Peng, et al.*, 2009; *Thomas et al.*, 2009; *Nadeau and Guilhem*, 2009] and (3) studies of the behavior of similar and characteristically repeating microearthquakes to investigate issues of earthquake scaling; deep (seismogenic zone) fault deformation and rheology; temporal changes in fault zone strength, state of stress, and fluid scatterer migration [*Chen et al*, 2007; *Dreger et al.*, 2007; *Taira et al.*, 2008]; and to test time dependent earthquake forecast models using the recurrence properties of actual events that recur on the order of months to years rather than decades to centuries, the numerous and frequently repeating characteristic microearthquake sequences [*Goltz et al.*, GJI, 2009; *Zechar and Nadeau*, 2009]. A list of publications is available upon request, which illustrate the significant use of the data from the borehole networks at Berkeley, and also at other institutions, nationally and internationally. The real time data acquisition from the regional and borehole networks, processing, notification and archival represent a continuum of necessary activities for earthquake monitoring and research in Northern California.

Prior to this project, most of the instrumentation for the BDSN and borehole networks was purchased and installed more than 10 years ago. Many elements of the system were aging, outdated and subject to failure. In particular, the station data loggers, which handle local data acquisition and real time telemetry, represented computer equipment that had several times exceeded its normal life expectancy; indeed, replacements no longer exist for failing parts for them. Some of the originally installed strong motion accelerometers are outperformed by more recently developed devices.

In this project, supported by funds from the America Recovery and Reinvestment Act (ARRA), we replaced old accelerometers and data loggers, and provided some telemetry improvements at the seismic networks operated by the BSL. The project contributed to the ARRA goals in two ways. First, this project allowed BSL to retain members of the technical staff despite significant cuts to the BSL's budgets from the University of California and the State of California. The purchase of equipment created job opportunities equivalent to about 10 FTE, nationwide. Second, this project helped the BSL continue to meet the ANSS goals for earthquake monitoring and reporting, for earthquake engineering purposes and for data archival. The new equipment has improved station reliability and the speed of data availability in real time. The new data loggers send data every second, improving their usefulness for earthquake early warning. In contrast to the old data loggers, the new ones can provide data from the accelerometers at 200 sps, which is of interest for engineering studies. At the same time, the new data loggers reduce maintenance efforts, as many equipment functions, such as calibration and centering, and troubleshooting can be performed remotely; field efforts, when necessary, will be better prepared by the remotely acquired knowledge of the station's problem. Station operation costs have been reduced, as the new equipment uses less power (fewer batteries for backup power, fewer solar panels), and for several stations, new, more robust and less expensive telemetry alternatives have been implemented. Thus, the high quality stations operated by the BSL in the BDSN, HRSN and NHFN will continue to provide data

for earthquake reporting, for engineering purposes, and for earthquake and earth structure research for the foreseeable future.

2. PROJECT IMPLEMENTATION

Project activites are best described by network: the broadband BDSN network, and the borehole networks (HRSN & NHFN). This is true for two reasons. First, the data loggers supplied as government furnished equipment (GFE) for the broadband stations are different from those for the borehole stations. Second, in an overarching sense, the station infrastructure and therefore installation logistics are different for the stations in these three systems.

2a. Berkeley Digital Seismic Network Upgrades

The BDSN currently comprises 35 stations, including an ocean-bottom broadband station in Monterey Bay (MOBB). Stations are equipped with three component broadband (STS-2, CMG-3) or very broadband seismometers (STS-1), three component strong motion accelerometers, and Quanterra station processors/data loggers that perform data acquisition and continuous, real time telemetry to UC Berkeley. Each station also has batteries to provide back-up power. The data loggers and batteries are configured to provide at least 3 days of back-up storage and power in the case telemetry or power fail. We take particular pride in high quality installations, which often have involved lengthy searches for appropriate sites far from sources of low-frequency noise, as well as continuous improvements in installation procedures and careful monitoring of noise conditions and problems. As a result, background noise at many of our sites is comparatively low.

Many of the BDSN stations were installed in the 1990's, starting in 1991 with a major upgrade effort supported by U.C. Berkeley. Prior to this project, most stations were operating with the original sensors and data loggers, representing various flavors of Quanterra equipment from the 1990's and early 2000's. With the exception of the ocean bottom station MOBB, which was recently equipped with a new custom-made data logger and connected to an undersea cable (MARS: http://www.mbari.org/mars/), only 5 recently installed stations, and one recently upgraded station (CVS) were equipped with state of the art Q330 or Q330HR data loggers. During the project, we also installed three new stations on the campus of the Lawrence Berkeley National Laboratory, in cooperation with and with instrumentation from them. Our plan was to replace 25 old data loggers with state-of-the-art GFE data loggers. Because our stations are generally quiet, we requested replacement data loggers that would provide matching low-noise characteristics, as well as compatibility of function and operation with our current Q330HR data loggers, including extra ports for environmental channels such as local temperature and pressure. We received 25 Q330HR data loggers and Baler 44 with 8 GByte storage on one memory stick to upgrade the 25 stations. The list of BDSN stations upgraded and the equipment installed at each site are given in Table 1. Each Baler 44 can accept two memory sticks, and be configured to switch between them, should problems occur on one. To enhance the capacity and robustness of onsite storage, we purchased additional 16 GByte memory sticks from ARRA funds. They have been installed at all sites except BRIB, BRK and PACP, the first three stations to be upgraded. We will install extra memory sticks at these stations during the next site visit. Upgrading the data loggers at most sites was not a trivial exercise of simply unplugging the sensors from the old data logger, removing it and connecting them to the new data logger, since the sensors are separated from the data loggers at most locations by up to several hundred feet. In addition, the cables for connecting sensors to a Q680/980 data logger are not directly compatible with a Q330HR. Thus, for most sites, we had to fabricate a cable adapter harness to connect the original sensor cables to the new data logger. For three sites with STS-1 seismometers, we were able to purchase Metrozet E300 electronics using funds from other sources. During the ARRA data logger upgrades at BKS, CMB, and YBH, we also installed E300 electronics, which allow remote calibration and recentering. A summary of

the equipment operating at the BDSN sites, including the ARRA-funded upgrades and improvements is given in Table I.

The upgrades with the ARRA equipment ensure that the stations will continue to operate reliably, producing high quality data in a timely fashion, and allowing remote data retrieval for intervals when telemetry has gone down. We are particularly keen on maintaining the low noise characteristics of our stations at periods longer than 20 s. These data are routinely used in real time moment-tensor inversions for earthquake magnitude and rupture orientation determination, as part of our contribution to the joint earthquake notification system with the USGS Menlo Park.

While accelerometers at many of the BDSN sites were progressively upgraded over the years, at the beginning of the project, 10 stations were still equipped with FBA-23 accelerometers. These are relatively noisy instruments, so they have limited dynamic range. They also have single-ended outputs, which do not work well with the differential inputs of stand-alone data loggers. The results are spurious noise on the accelerometer traces. We received 10 Kinemetrics FBA ES-T accelerometers as GFE with which to replace them. For the stations which required them, they were installed during the same visit in which the data logger was replaced (Table I).

The last of the data logger replacements, with the exception of KCC, was completed in June 2011, with the installation of the Q330HR plus Baler 44 at station YBH. The Q935 data logger at KCC failed in December 2009, just before we received the GFE data loggers for the ARRA project. We replaced it "temporarily" with a BSL-owned Q330HR plus Baler 14. When we returned to KCC to replace it with a GFE data logger, we were not allowed access to the site, because of a hazardous, broken water conduit in the Southern California Edison tunnel. We will install the GFE data logger at KCC at the first opportunity.

Telemetry is a major expense in the network operations budget. Data from most of the BDSN stations are telemetered by frame relay connections to the data center. The annual cost of a single frame relay circuit is over $1200 per year. We used ARRA funds to purchase equipment and installation services to replace frame relay telemetry for two BDSN stations, JRSC and MNRC. JRSC is on Stanford University's Jasper Ridge Reserve. Just prior to this project, Stanford installed a microwave internet link between the Reserve and Stanford's main campus. For JRSC, the seismic station was connected to the microwave internet link, and the data are now returned to Berkeley at no cost. For MNRC, data from the station arrived at Berkeley through two radio hops and a frame relay circuit. The radio repeater was hosted on a communications tower of the California Division of Forestry (CDF) and the frame relay drop was at a CDF fire station. We paid the CDF $1500 per year in rent for the use of the two sites. While the replacement telemetry for MNRC, Wild Blue satellite internet services, costs about the same as the frame relay circuit which has now been discontinued, we no longer pay the fee to CDF, reducing the ongoing cost for data from that site.

2b. Borehole Network Upgrades

The BSL operates two networks of borehole stations, thirteen stations of the HRSN in Parkfield and 15 in the Bay Area (NHFN). Only nine of the NHFN stations are supported by the USGS, the others are operated in cooperation with Caltrans, and with funding from them. We requested 6-channel, high sample rate (minimum 500 or 1000 sps) data loggers with high resolution and having causal anti-aliasing filters, but using less power than the aging Q730s and Q4120s installed at the borehole stations. A particular advantage of new data loggers is their low power requirement, which increases their reliability at the solar powered HRSN stations. There are several reasons that it is important to have a single type of data logger for all the borehole sites. The first is interchangability: it is easy to replace malfunctioning equipment at one station with that from another. It also reduces the complexity of the system by having a single standard for station programming. We received 22 GFE eight-channel Kinemetrics Basalt data loggers for the borehole stations in the Summer of 2010. Summaries of the equipment operating at the BSL's borehole stations is given in Table II (Parkfield boreholes) and Table III (Bay Area boreholes).

Box 1: Learning about the Kinemetrics Basalt

1. The Kinemetrics Rock MiniSEED module did not support STEIM2 data compression, which was highly desireable given the high sample rate (500 sample-per-second) used by the BSL. Kinemetrics added STEIM2 support to their Rock MiniSEED data archiving module.

2. The Rock software did not provide support for setting the SEED channel name, SEED network, and SEED location code for the various state-of-health (SOH) channels such as system voltage, system power, clock quality, clock phase, mass positions, etc. After discussions between BSL and Kinemetrics on these requirements, Kinemetrics added support for users to optionally specify the SEED Station, Network, Channel, and Location for all SOH data channels. The full SEED names are now available to all Rock modules, including the ISTI-written Earthworm and SEEDLink telemetry modules.

3. The ISTI SEEDLink module did not support STEIM2 compression. Since the SEEDLink modules acquires data directly from the Rock digitizer module for minimal latency, it does not use the Rock-supplied MiniSEED data archving/conversion module. The BSL supplied ISTI with STEIM2 compression code written in java, and ISTI added the STEIM2 into their SEEDLink telemetry module.

4. BSL discovered discrepencies between the timeseries telemetered using the ISTI SEEDLink server and the data stored locally on the Basalt by the Rock MiniSEED Data Archiver module. We determined that this is a result of the Rock software design that transforms all data into a uniformly sampled timeseries by discarding apparent overlapping data samples and inserting samples with 0 amplitude for apparent missing data samples whenever there is a clock correction or timing jump. This is done in order to support Rock data archiving and data data handing in formats thatc cannot represent breaks or discontinuities in timing. After discussing the problem with Kinemetric, they created a new Rock Module "SLinkMirror" that receives MiniSEED data packets from the ISTI-supplied Rock SEEDLink server and archives the MiniSEED data on the Basalt's local disk. This creates a local onsite data archive that is identical to the telemetered MiniSEED records. All data samples are preserved, and timing discontinuitues are preserved to allow proper post-processing timing corrections.

5. Using BSL funding, ISTI added support for an optional telemetry (data logger) name for its SeisNetWatch agent. This allowed the BSL to uniquely identify each data logger at sites that have multiple data loggers that conform to the SEED standad of a single SEED station name for all data channels at that site.

6. The BSL discovered that the Basalt data loggers were prone to numerous reboots at solar-powered sites and occasional reboots at all sites due to apparent low voltage conditions, even when the SOH channels indicated sufficient voltage. Kinemetrics provided us with updated configuration parameters for the embedded Basalt power modules that have largely alleviated this problem.

7. The BSL discovered that that digital signal processors (DSPs) in the analog-to-digital (A/D) systems in the Basalt were randomly restarting for no apparent reason, which caused a break in the time series and a loss of data. We provide debugging output to Kinemetrics, and tested multiple versions of their Rock firmware in an attempt to identify and and remove the source of this problems. Kinemetrics currently believes that the problem resides within the Java Virtual Machine (JVM) or the compiler used to build their DSP code, and is working to address this outstanding problem.

Having no field experience with the Basalt data loggers, we spent almost 3 months testing them in house, to determine appropriate configurations for operating them at our various sites. During this time, we discovered problems with the firmware and suggested several software and configuration improvements to their operating systems, which were implemented by Kinemetrics and ISTI (see Box 1). Installations of the data loggers at borehole sites were completed by October 2011, with the exception of stations RMNB in Parkfield and CMSB in the Bay Area. For RMNB, we never received permission from the landowner to enter the property. Sadly, we do not know if we will be able to revisit this station. We are no longer receiving data from it. CMSB is next to the north end of UC Berkeley's California Memorial Stadium. The stadium is currently undergoing a massive retrofit and renovation project. Our access to the site was cut when the construction began, and we were required to remove the surface equipment at that time. We will install the data logger and reinstall power and telemetry equipment when the construction project allows. This site, which was served by frame relay will then rely on the University's network services, reducing telemetry expenses.

All the stations of the HRSN are solar powered and have radio telemetry to the CDF station in Parkfield. From the CDF station, the data return to UC Berkeley via the USGS microwave circuits. Using funds from the ARRA project, the power systems at all HRSN sites were refurbished, with additional

Table I:

UCB Operated Seismic Stations: Digital Dataloggers, Sensors and Related Equipment - BDSN								
Network Code	**Station Code**	**Existing / Replaced Acquisition System**	**Existing High-gain Sensor**	**Existing / Replaced Strong-motion Sensor**	**GFE Acquisition System Installed**	**GFE Broadband Sensor Installed**	**GFE Accelerometer Installed**	**Comments**
BK	BDM	Q4120	STS-2	FBA-23	Q330HR, baler	N/A	FBA ES-T	
BK	BKS	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	Metrozet E300 electronics installed for STS1 (funded from other sources)
BK	BL67	Q330S	N/A	FBA ES-T	N/A	N/A	N/A	Installed April 2011; Equipment provided by Lawrence Berkeley National Laboratory (LBNL)
BK	BL88	Q330S	CMG-3T	FBA ES-T	N/A	N/A	N/A	Installed January 2011; Equipment provided by LBNL
BK	BRIB	Q935	CMG-3T	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	BRK	Q935	STS-2	FBA-23	Q330HR, baler	N/A	FBA ES-T	
BK	CMB	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	Metrozet E300 electronics installed for STS1 (funded from other sources)
BK	CVS	Q330HR	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	FARB	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	GASB	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	HAST	Q330HR	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	HATC	Q330HR	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	HELL	Q330	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	HOPS	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	Metrozet E300 electronics installed for STS1 (funded from other sources)
BK	HUMO	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	JCC	Q935	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	JRSC	Q680	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	Frame relay telemetry replaced by wi-fi, Stanford University microwave and internet.
BK	KCC	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	UCB-owned Q330HR installed shortly before GFE equipment arrived, due to failure of the Q935; the GFE data logger has not yet been installed, as we cannot currentl access the site; Metrozet E300 electronics installed for STS1 (funded from other sources)
BK	MCCM	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	MHC	Q935	STS-1	FBA ES-T	Q330HR, baler	N/A	N/A	Metrozet E300 electronics for STS1
BK	MNRC	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	Radio and frame relay replaced by Wild Blue satellite
BK	MOBB	CMG-DM24	CMG-1T	N/A	N/A	N/A	N/A	Ocean bottom station
BK	MOD	Q935	STS-1	FBA ES-T	Q330HR, baler	N/A	N/A	High gain sensor is currently STS-2; the STS-1s have been refurbished and will soon be replaced.
BK	ORV	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	
BK	PACP	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	PKD	Q935	STS-2	FBA-23	Q330HR, baler	N/A	FBA ES-T	
BK	RAMR	Q330	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	RFSB	Q730	N/A	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	SAO	Q935	STS-1	FBA-23	Q330HR, baler	N/A	FBA ES-T	Metrozet E300 electronics for STS1
BK	SCCB	Q730	N/A	TSA	Q330HR, baler	N/A	N/A	
BK	SUTB	Q330	STS-2	FBA ES-T	N/A	N/A	N/A	
BK	VAK	Q330S	CMG-3T	FBA ES-T	N/A	N/A	N/A	Installed Aug 2010; Equipment provided by Lawrence Berkeley National Laboratory (LBNL)
BK	WDC	Q935	STS-2	FBA-23	Q330HR, baler	N/A	FBA ES-T	
BK	WENL	Q4120	STS-2	FBA ES-T	Q330HR, baler	N/A	N/A	
BK	YBH	Q935	STS-1	FBA ES-T	Q330HR, baler	N/A	N/A	Metrozet E300 electronics installed for STS1 (funded from other sources)

solar panels where necessary and with new batteries. The batteries at these locations suffer particularly because of the very high temperatures in the summer, and the low temperatures and often very short charging times during the winter days. The HRSN sites are far from ideal for radio telemetry, although there is no other option. Data from several of the sites go through two repeaters. The telemetry links were upgraded with ethernet radios for compatibility with the new ethernet-based telemetry of the Basalts. For the HRSN sites, the fabrication of cable adapter harnesses was necessary to connect the BSL-designed preamps with the Basalts. Prior to the ARRA project, rodents had damaged the HRSN site JCNB just above the wellhead at a depth of 30 ft. Unfortunately the damaged point was inaccessible and could not be repaired. Using ARRA funds, we purchased a 10 Hz geophone package and deployed it, along with the GFE data logger to bring this station back online. The hole was backfilled with sand. Currently, 12 stations of the HRSN have been upgraded and are operating.

Table II:

Parkfield Borehole Seismic Stations Upgrades: Digital Dataloggers and Sensors and Related Equipment: UCB -HRSN								
Network Code	**Station Code**	**Existing/ Replaced Acquisition System**	**Existing High-gain Sensor**	**Existing Strong-motion Sensor**	**GFE Acquisition System Installed**	**GFE Broadband Sensor Installed**	**GFE Accelerometer Installed**	**Comments**
BP	CCRB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	EADB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	FROB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios and power system replaced
BP	GHIB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios and power system replaced
BP	JCNB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Sensor cables had been broken. We installed a 10 Hz geophone, replaced telemetry radios and upgraded the power system.
BP	JCSB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	LCCB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	MMNB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	RMNB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Equipment was not replaced; as we did not receive the landowner's permission to visit the station
BP	SCYB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	SMNB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	VARB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced
BP	VCAB	Q730	L22	N/A	8 channel Basalt	N/A	N/A	Telemetry radios replaced; batteries replaced

Table III:

Bay Area Borehole Seismic Stations: Digital Dataloggers and Sensors and Related Equipment: UCB NHFN								
Network Code	**Station Code**	**Existing/ Replaced Acquisition System**	**Existing High-gain Sensor**	**Existing Strong-motion Sensor**	**GFE Acquisition System Installed**	**GFE Broadband Sensor Installed**	**GFE Accelerometer Installed**	**Comments**
BK	BRIB	Q4120	Oyo GS-11	W731A	8 channel Basalt	N/A	N/A	
BK	CMAB	Q4120	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans
BK	CMSB	Q4120	Oyo GS-11	W731A	8 channel Basalt	N/A	N/A	Surface equipment removed due to retrofit project at Cal Memorial Stadium; station will be reinstalled with GFE when construction is completed.
BK	HERB	Q4120	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans
BK	MHDL	Q4120	L22	N/A	8 channel Basalt	N/A	N/A	
BK	OHLN	Q4120	L22	N/A	8 channel Basalt	N/A	N/A	
BK	OXMT	Q4120	L22	N/A	8 channel Basalt	N/A	N/A	
BK	PETB	Q330	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans
BK	RB2B	Q4120	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans
BK	RFSB	Q4120	Oyo GS-11	W731A	8 channel Basalt	N/A	N/A	
BK	SBRN	Q4120	L22	N/A	8 channel Basalt	N/A	N/A	
BK	SM2B	Q4120	Oyo GS-11	W731A	8 channel Basalt	N/A	N/A	
BK	VALB	Q330	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans
BK	W02B	Q4120	Oyo GS-11	W731A	N/A	N/A	N/A	Operated in cooperation with Caltrans

Table IV:

Comp	STS-1/E300 ($\mu m/S^2$)	STS-2 ($\mu m/S^2$)	Episensor ($\mu m/S^2$)	% difference (STS-2/Epi)	Scale Factor (STS-1/STS-2)
Z	37.281	45.537	45.526	0.024	0.81870
N	41.736	41.112	41.035	0.19	1.01518
E	57.395	47.464	47.109	0.75	1.20476

2c. Metadata, Sensor Calibration, Polarities and Orientations, and SEED Channel Naming

Metadata and sensor calibration are important for all our seismic stations, while the determination or validation of sensor polarities and orientations are important for the borehole stations. We do not use premade cables at most of our sites. In some cases, the sensors are installed at some distance from the data loggers to reduce sources of noise. At others, such as the borehole locations, the sensor cables are not standardized. Particularly at many of the borehole stations, the original connection of the sensors to the data loggers was made on an "ad hoc" basis – i.e. the connections were made and the orientations and polarities of those connections were determined later. For this project, our goal, in terms of orientation and polarity, was to ensure that the broadband/strong motion conform to ANSS standards. We also made efforts to determine or redetermine the calibration parameters, particularly for the STS-1 sensors. For the borehole sites, we decided that maintaining "historical" polarities, orientations and channel assignments was more important than correcting them. We also took advantage of the upgrades to transition our channel naming convention and to apply non-blank location codes to all our channels.

Metadata evaluation and response: When GFE equipment, whether data logger or accelerometer, was installed at a seismic station, metadata were updated and made available within 24 hours. This was an important step, as we produced cable harnesses to connect sensors to the new data loggers. Equipment parameters such as digitizer and accelerometer sensitivities were taken from the instrument-specific calibration sheets. Data from the new data logger immediately began flowing into our real time processing systems. The performance of the equipment and the metadata were evaluated using the next large teleseism or regional earthquake. Several waveform comparisons were performed. For regional earthquakes, data from the broadband sensor was compared with that of corresponding channel of the strong motion sensor. For teleseisms, waveforms from the broadband channels were compared with those of nearby broadband stations. In most cases, this evaluation confirmed that all information was correct, and that everything was working properly. In two cases, at PACP and BKS, we found that sensor channels had been connected to the wrong data logger input channels. As soon as the discrepancies were noticed field visits were scheduled to rectify the problem. Renewed evaluation proved that the problems had been corrected.

Sensor calibration: During the ARRA upgrade process, several stations with STS-1 broadband sensors were also upgraded with E300 electronics purchased from other funds. For these stations, a separate sensor calibration procedure was necessary, as the instrument-specific calibration sheets were no longer applicable. We used the E300 sweep calibration to determine corner periods and damping for the STS-1 sensors. Nominal sensitivities are available for the STS-1/E300 combination through an applet provided by Metrozet, the electronic's manufacturer. This applet calculates the new sensitivities based on knowledge of the original STS-1 electronics for that particular sensor. We used the applet to calculate the nominal sensitivities, and then compared waveforms for the STS-1/E300 and the accelerometer for regional or teleseismic earthquakes using those parameters. In the case of the seismometers at our station CMB, the match was excellent (<1% difference) for all components between the STS-1/E300 and accelerometer. For the station YBH, there were discrepancies of up to a factor of 25% (see Table IV). These were confirmed once the data logger for the CTBT STS-2 was installed in October 2011. For the STS-1 at YBH, we use the revised sensitivities determined by the comparison of the STS-1 channels with those of the other co-located sensors.

Polarities and orientations for borehole channels: For the boreholes stations, we chose to maintain historical consistency for channel polarities and orientations. Our catalogs of repeating earthquakes are the tool we used to evaluate these two parameters. We describe the borehole channels as "1, 2 and 3" rather than as "Z, N and E", since we do not know their exact orientation within the borehole. To maintain orientation means that the assignment of "1, 2 and 3" to the sensor channels connected to the data logger maintain the similarity of waveforms for any particular repeater sequence. That is, we compare the "1" channel after the upgrade to the "1" channel before. If we find the same waveform, then the channel orientation is consistent. If the waveform is similar but has opposite amplitudes, the polarity is reversed. In fact, this was perhaps the most difficult part of the upgrade, as our historical documentation of

connections between sensors and data logger channels, through preamps when present, was very poor. The necessity of fabricating cable harnesses to connect to the new data loggers provided an additional opportunity for discrepancies. The miniPBO sites (MPBO, Figure 1), which were installed in the past 10 years all had the same wiring. Thus, once the correct connections were determined, matching harnesses could be produced for them. For the Parkfield stations, initial data logger exchanges produced inconsistent channel connections, and several field trips were dedicated to resolving and correcting cable connections to produce the correct orientations and polarities. In the Bay Area, repeating events do not occur as frequently, so for some stations, we are still awaiting new events to confirm channel assignments and polarities.

SEED Channel Naming: SEED conventions are updated regularly. In two respects, it has been the goal at the BSL to bring our channel naming into compliance with new standards. Since the ARRA-funded upgrades produced a watershed in our recording and archival, we took the opportunity to apply the new standards. With each upgrade, accelerometer channels were renamed from "?L?" to "?N?", for example new data from channels previously named HLZ are now found under HNZ in the data center. Secondly, we now no longer operate any channels with blank location codes. For our standard ANSS-type station, the location code is "00". Downhole sensors at borehole stations have location code "40". The CTBT STS-2, a second high-gain seismometer at our station YBH, has the location code "50". Its channels are now named "HHZ, HHN, HHE" and no longer "HH1, HH2, HH3".

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