Final Report 2010 - 2015
USGS Cooperative Agreement for Seismic Network Operations:
Operation of the Northern California Earthquake Management Center,
and the UC Berkeley Seismic Networks
Cooperative Agreement G10AC00093

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Network Names: *Berkeley Digital Seismic Network, High Resolution Seismic Network, Northern Hayward Fault Network* Web Site: http://earthquakes.berkeley.edu Network Codes: *BK, BP* ANSS Region: *California*	Data Center: *Northern California Earthquake Data Center (http://ncedc.org)*
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University of California Berkeley Seismic Network and Data Center Summary

This cooperative agreement provides support for the UC Berkeley Seismological Laboratory's (UCB) contribution to operating the earthquake monitoring and information system in the Northern California Earthquake Managment Center (NCEMC). The NCEMC effort is a joint operation of the USGS Menlo Park (USGS MP) and UCB, with the joint earthquake reporting system called the Northern California Seismic System (NCSS). The agreement also provides support to develop, maintain and operate the realtime and datacenter (public) database systems both at the USGS MP and at UCB; and to support operations of the Northern California Earthquake Data Center (NCEDC), the permanent repository for all data, metadata and parametric data generated and used within the NCEMC. The agreement includes operating support to UCB for the seismic stations it operates, including borehole stations (Figure 1). The borehole networks are the High Resolution Seismic Network in Parkfield (HRSN, network code BP) and the Northern Hayward Fault Network in the Bay Area (NHFN includes some miniPBO sites). The NHFN stations operate under the network code BK along with the broadband/strong motion stations of the Berkeley Digital Seismic Network (BDSN). Data from all borehole sites have been contributing to real time earthquake monitoring since before the transition to AQMS software in June 2009. Table 1 details seismic information archived at the NCEDC.

Among other activities and earthquakes which occcured during this five year project, successful reporting of the NCSS on the South Napa earthquake (24 Aug 2014) highlights the collaboration between UCB and USGS MP to provide rapid earthquake information to government organizations, researchers and the public, and to make high quality data available for all purposes. Earthquake early warning information on the event was available through CISN ShakeAlert within 5.1 s of the origin. All earthquake information products were submitted to PDL shortly after they were produced, and were available through various websites. An automatic moment tensor was released and then reviewed. A finite fault solution (UCB) was also produced automatically within 10 minutes of the origin time and reviewed. ShakeMap, ground motion packets and V0 files for engineering use were also produced, published and shared. The ShakeMap production process pointed out processing challenges that were quickly corrected. During the rapid response to this quake, a number of temporary stations were deployed, primarily by colleagues at USGS MP. Data retrieved from these stations have been incorporated into the NCEDC data holdings and added into the event waveform collections for the aftershocks, mainly due to efforts of the UCB team.

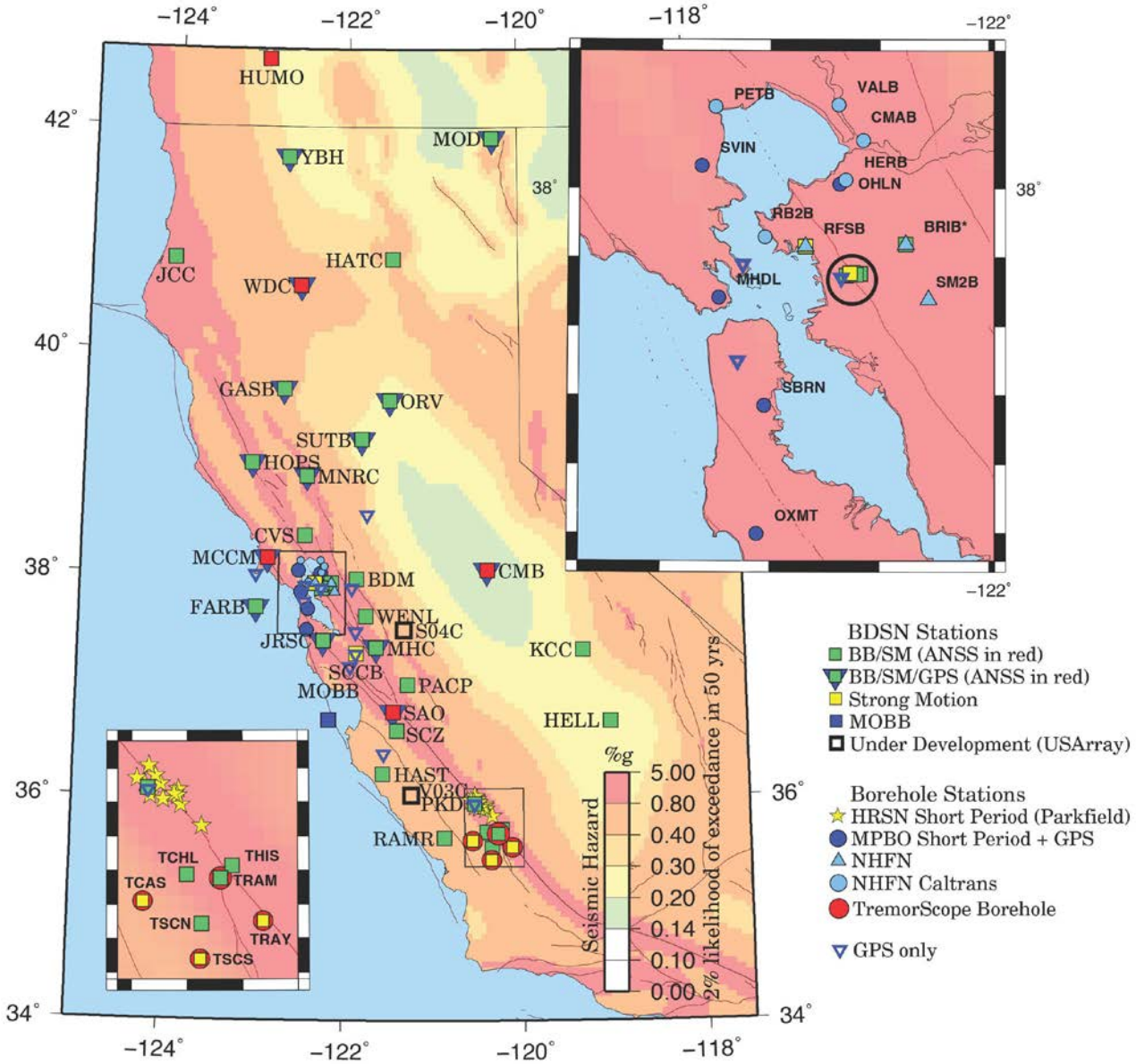

Figure 1. Map of Seismic Stations operated by the UC Berkeley Seismological Laboratory in Northern California. In addition to the ANSS Backbone and GSN stations (HUMO, CMB, SAO, MCCM, WDC), the BSL contributes data from HOPS, JCC and ORV JCC, MOD, ORV and YBH to the NEIC in near realtime. Data loggers at 25 and accelerometers at 10 of the broadband/strong motion stations are government furnished equipment (GFE). We recently also received Baler44 from the ANSS Depot to upgrade from Baler14 at 8 sites. Data loggers at 12 HRSN sites and at 8 Bay Area borehole sites are GFE. The Cal Memorial Stadium Seismic Upgrade Project was completed in August 2012, but at the very end of the project, the construction crew "lost" our borehole. A new borehole has been drilled nearby, and new equipment purchased by the University for installation is being tested. It will be installed soon. Stations TCHL, THIS, TSCN and TRAM are broadband/strong motion surface stations funded by the Moore Foundation as part of the TremorScope project. Four boreholes have also been drilled for the TremorScope project; a geophone is now deployed in one of them, data will also soon be arriving from the others. TremorScope data flow into the realtime monitoring system courtesy of the USGS Menlo Park microwave telemetry system. Stations in the circle in insert on the upper right are: BRK, BL88, VAK, BL67 and BKS (from west to east). We will soon be installing a broadband/strong motion station in the Lawson Adit on Campus. In addition to the 5 mPBO sites with realtime GPS (OXMT, SBRN, SVIN, MHDL, OHLN), 17 of the BDSN's broadband/strong motion stations also have colocated continuous GPS equipment supported by the Bay Area Regional Deformation (BARD) Network Cooperative Agreement.

Table 1: Summary of Archival Stastics for Seismic Stations in and Contributed to the NCSS

Summary Statistics	Number	Station Response Information in dataless SEED volume(s)
Total no. of stations operated and/or recorded	62	SEED responses for all SNCL's we record are available through web services at the NCEDC (http://service.ncedc.org/fdsnws/station/1/) the ftp site http://www.ncedc.org/ftp/pub/doc/ We record data from about 20 networks. The SEED volumes are in the subdirectory labeled by each network name and then by "Network.responses" or "Network.dataless.seed", then by SNCL name[#]. The NCEDC is now the official repository for metadata for all NP stations.
Total no. of channels recorded	1,846/19,704[&]	
No. of short-period (SP) stations	26	
No. of broadband (BB) stations	41 (one is BB only, 3 are SM only)	
No. of stations maintained & operated by network	62	
No. of stations maintained & operated as part of ANSS	5/62[%]	

& These are the total number of unique channels (unique "station.network.channel.locationcodes", or SNCLs) recorded in the past year at the NCEDC. The first number is for SNCLs with either BK or BP as network codes, stations the BSL operates. The second number includes data collected at the USGS MP and forwarded for archival to the NCEDC, as well as data from other stations collected and used by the BSL. We archive data from more than 15 other seismic networks. Both numbers include state-of-health channels where available.

% Five stations from the BK network are ANSS backbone stations. In addition, we operate one GSN station (CMB). We contribute real time data from 10 stations (including ANSS and GSN) to world-wide earthquake monitoring at NEIC; we contribute data from 10 stations to ATWC and data from 12 stations to PTWC to support their monitoring efforts. Data from all BK and BP stations are used in earthquake monitoring activities in the Northern California Earthquake Management Center, the joint operation of the BSL and USGS MP as part of the California Integrated Seismic Network of the ANSS. We also use data from neighboring networks, like NN, stations from the Cascadia Initiative (TA), from the Plate Boundary Observatory (PB) and from the Southern California Seismic Network (CI) in our earthquake monitoring and information system.

For a very small number of the SNCLs for which we have waveforms in the archive, we currently do not have metadata.They are "historical" BK stations which predate the era of digital telemetry. We are working to develop metadata for these BK SNCLs.

The following sections describe activities and highlights from the past five years.

1) *Operation, improvement, fine tuning and software support for the ANSS Quake Monitoring System (AQMS) software for Northern California (and other regional networks).*

In June 2009, the NCEMC made the transition to using the AQMS software for monitoring earthquakes and publishing earthquake information in Northern California. UCB personnel provides most of the expertise to operate, maintain and support both the day-to-day operations of the composite system, to fine tune the parameters controlling the system, and to develop improvements and prepare fixes to it. This work includes operating, maintaining and upgrading the Oracle databases which are fundamental to AQMS operation. In the NCEMC, two parallel systems operate continuously, one in Menlo Park and a second at UCB, each system having one realtime database and one datacenter database. At any given time one of the systems is authoritative, with the second providing backup. We switch between the systems regularly as updates and patches are applied to the software and operating systems. The datacenter databases replicate with each other and with the public database, to ensure that all information is up-to-date in all databases. The public database, which is hosted at UCB, provides information to the public.

Since the transition, we continue to improve and fine tune the parameters of the AQMS system, and upgrade software, operating systems and the database to incorporate patches. In addition to supporting the earthquake monitoring software, UCB has provided extensive computer systems support to the USGS MP team during the project to help patch and upgrade computers and operating systems, as well as in support of the transition to the operation of AQMS from computers running Solaris to linux. The latter transition will reduce costs in the long run, as Solaris licenses will no longer be requiried. In addition, we upgrade and replace computers, networking hardware and disk systems as necessary, to maintain robust operation. These support activities contribute to the robustness of our joint earthquake information system.

During the five years of this project we have had several opportunities to test "continuity of operations" procedures, either in planned or unplanned events. Both UCB and USGS MP have had planned data center curtailments, either for testing backup power systems or during other data center upgrades. An example of an unplanned "test" occurred at the beginning of the goverment shutdown in 2013. At that time, UCB was master, as none of the USGS MP colleagues were permitted to work. A power failure affected the entire UC Berkeley campus that evening. Although the UCB AQMS data center continued to function, as the backup power systems in Warren Hall kicked in, the air conditioning there did not respond properly. Temperatures climbed in the data center, and some of our operational computers shut down. To ensure reliable earthquake reporting, we made the Menlo Park computer systems master until later in the evening when power was restored at UCB. During that time, there was no online "Duty Review Page" (DRP) for reviewing earthquakes, because our Menlo Park partners had not yet been able to acquire the firewall holes needed to allow access to a webserver. That problem has been alleviated, and there are now DRPs on both sides of the Bay.

Developments and improvements we have made to the AQMS processing system during this project include the following.

Implementing PDL (Product Data Layer) for publishing all earthquake products to Earthquake Hazards Program (EHP) computers, including the historical catalog: UCB was the "intial adopter" of PDL for publishing ShakeMap. The UCB provided signifcant development effort toward data submission to the new ANSS Comprehensive Catalog (ComCat) using the new Product Distribution Layer (PDL), and provided timely feedback to the EHP development team on both PDL and QuakeML issues. We developed an flexible XML writer for AQMS systems that can generate QuakeML for any or all of the following PDL products:

a. Origin products (hypocenter and magnitudes)
b. Phase products (hypocenter, magnitudes, phase, and amplitudes readings)
c. Mechanism products (mechanism information with related gif images)
d. Moment tensor products (moment tensor information with related gif images).

BSL continues to enhance the qml program used by AQMS systems to construct QuakeML files for submitting event information to the ANSS Comprehensive Catalog (ComCat). The qml program can generate origin products, phase products, and/or mechanism products from any event from an AQMS event database, and is used by multiple ANSS regions to submit real-time data to the ComCat.

Teleseism Stifler: We implemented an improvement to the AQMS system's ability to prevent publication of false local events created from P-wave (and possibly other) arrivals from strong (deep) teleseisms. This is a perennial problem for the system. The model we adopted collects information about teleseisms produced by NEIC, ATWC or PTWC and published through PDL. This "teleseism stifler" allows configuration parameters such as minimum teleseism magnitude, event distance and blockout window interval to be tuned. During a time window around the expected P-wave arrival, the stifler "mutes" publication of information for moderate local events (M>3.5) to the web and the public. It also alerts the duty seismologist to the situation and requests that he or she immediately review the events produced by AQMS. If the seismologist confirms that is really is a local event, it will then be published. Other regional networks are now using our "tele-stifle" code with great success.

AQMS under Linux: In response to the interest of many network operators for having a version of AQMS that runs under linux, we have compiled and tested it. Unfortunately, C++ works differently under Linux and Solaris. Pete Lombard, who is spearheading the work at UCB, found and corrected some bugs. After considerably compiling and testing, Pete Lombard posted the code package to the software repository for further testing in Southern California, where the instance of AQMS is different than that in Northern California. Southern California is now using the Linux package that Pete Lombard developed to move all AQMS processing to Linux. BSL continues its testing and migration of AQMS systems from Solaris to Linux operating system. Since most production AQMS systems at the BSL have been running on X86/64 computer hardware, the migration to Linux does not involve complete replacement of hardware, but only testing and certification of the ported software to Linux, and a phased migration of existing AQMS system from Solaris to Linux. This is an ongoing task which is being coordinated with our NCEMC partners at the USGS Menlo Park.

Support for AQMS at other regional networks: UCB personnel have participated actively in supporting the implementation and configuration of AQMS by other networks. We continue to answer questions by email or phone as other network operators implement and configure their systems. Most recently, Pete Lombard helped the PNSN operators get their AQMS systems back up on a Saturday morning, after both had failed on Friday evening.

This support includes inviting members from other regional networks to participate in and contribute to the "CISN" working groups on Standards, Schema Change, ShakeMap, etc, as necessary to improve AQMS for their operations.

QMAserve/comserv: Data from Quanterra data loggers is passed from one processing step to another via a program called *comserv*, now *qmaserv*, developed at UCB. As operating systems and computer types proliferated, a new version was developed to run under the new conditions. The two programs for all the various systems have now been repackaged to a single software release with documentation. It is available via ftp.

Waveform rerequest tool for Jiggle: Jiggle is the program used to analyse and review earthquakes in the AQMS system. One recurring problem that analysts encounter, is that the waveforms associated with an event or trigger do not include the appropriate time windows of data. In the past, NCSS analysts have collected a list of events with approximate origin times, and new sets of waveforms were manually requested for these events, a painful and circuitous process. Pete Lombard developed an extremely useful tool to automate the proceedure. Now any Jiggle user can automatically request a new set of waveforms for a specific event, based on the new, approximate origin time determined in Jiggle.

SIS and StationXML development: BSL staff actively participate in the ANSS Station Information System Technical Impementation Committee (SIS TIC) which defined and refined the requirements, scope, and implementation of SIS. In addition, BSL and CIT staff jointly developed the extended Station XML specification that provides a description of the hardware components of each station, the cabling of sensors to data acquisition system, the analog-to-digital (A/D) components, and the digital filters and decimation description of all data streams generated by the data loggers. This format is being used for both importing initial station and hardware information into SIS as well as exporting information from SIS to be loaded into database for use in AQML real-time data earthquake detection and processing systems as well as data distribution systems. USB staff assumed responsibility for developing the software to create extended station XML from AQMS database for importing station information into SIS, and for developing the software and procedures for importing extended station XML files produced by SIS into AQMS hardware tracking database for use by AQMS and Earthquake Early Warning systems. This process is still under active development, and we work closely with the SIS developers at CIT to test and implement the data flow between AQMS and SIS. The NCEMC has not migrated its station information into SIS since SIS still does not have key features required by the NCEMC for the maintenance of historic (non-current) station information. These maintenace features are in the development plan for SIS, and BSL staff is working with the CIT SIS developers to define and refine these procedures.

Improving M_L reporting: Several years ago, we completed a project to unify M_L determination in California using the horizontal components of broadband and strong motion sensors. It has been in operational use statewide since 2009. We are now expanding the calibration to include vertical broadband and strong motion channels as well as vertical and horizontal components of short period seismometers and geophones. We have collected a data set of both small (M1.5-1.8) and moderate (M3-3.2) events and have processed them to determine "Wood-Anderson amplitudes", the basis for M_L determination. We have completed the inversion and are reviewing the results, before presenting them to the CISN group. This is of particular value in Northern California, where the network of BB/SM stations is relatively sparse. When the new calibration is complete, we will be able to determine magnitudes for much smaller events than we currently can. Duration magnitude, which we normally use for small earthquakes, "saturates" because the coda is too short for the standard measurement procedure.

2) *Operation of the Northern California Earthquake Data Center, the authoritative repository for Northern California seismic data from the USGS MP and from UCB.*

The NCEDC archives data from the BK and BP networks of UCB. It also archives data from all the stations collected by the USGS MP, including the NC network, the Geysers network operated by Lawrence Berkeley National Laboratory (LBNL) (BP), data contributed by PG&E (PG), by the California Geological Survey (CE), the California Department of Water Resources (WR), the University of Nevada, Reno (NN), the Southern California Seismic Network (CI), the National Strong Motion Program (NP). Other data are archived from the Plate Boundary Observatory (PB), the San Andreas Fault Observatory at Depth (SF), as well as from 6 networks for monitoring geothermal areas collected by LBNL. Data holdings now consist of almost 88 terabytes of data (Table 2).

The Oracle public database for AQMS resides at the NCEDC. This database is the repository for all event related information, including hypocentral location, and associated information such as picks and amplitudes as well as mechanisms and magnitudes. Catalog information goes back to 1932. We are working to merge catalog information from the BK and NC networks for the years from 1966 – 1999. At the same time, we have been working toward the AQMS software to conform with the new depth reporting requirements, and will recalculate all the Northern California locations in the NC catalog to give geoid depths. There are no quakes in the catalog for which we cannot calculate a geoid depth. We expect to complete the process and hope to submit the NC catalog for 1974-present to to ComCat in the next 6 months.

We continue to improve data access capabilities. For example, we upgraded the full waveform DART feed (Data Available in Real Time). We also developed, tested and released a new version of swc (simple waveform client) software package that allows retrieval of data from the NCEDC. Data are available to users through a variety of

Table 2: Data Center Holdings and Data Distribution

Holding Format	Terabytes
Continuous waveforms (mseed)	**80.9**
Event gathers (mseed)	**1.4**
EGS event gathers (mseed)[1]	**0.5**
GPS[2]	**4.9**

Data Distributed[3]	Terabytes
Assembled datasets	0.03
Catalog data	28.8
Continuous/event mseed	17.7
GPS[2]	0.6[2]
Raw data[4]	0.01
XML data[5]	0.002

1 EGS = Enhanced geothermal system earthquakes
2 GPS = Geodetic positioning system. Data distributed does not include data immediately served through our Ntrip caster.
3 Data Distributed = Does not include any data exchanged in RT exchange with MP, PAS, UW, ATWC, PTWC, Golden, or other partners.
4 Raw data = original data from strain and other sources, converted to mseed for distribution. Original data are always retained and can be distributed.
5 XML data = These include station information and PBO Strain XML data

means, including new network services. Various other improvements have been and are in the process of being made at the NCEDC during the project, some but not all of them have been funded in part or in full by the cooperative agreement. They include

- *Storage management and data copies*: The NCEDC uses the SAMFS/ZFS hierarchical storage management software to manage waveform storage. During the project SAMFS was upgraded to to ZFS, which allows unlimited amounts of data to be served by a 4 CPB (8 core) computer system. ZFS can automatically create up to 4 copies of each data file on different storage systems and media. We create one copy of all waveform data on RAID disk for rapid access, one copy on LTO tape which is kept online in the tape library, and one copy on LTO tape which is stored offsite. Should a RAID system ever fail, the ZFS system can automatically rebuild the disk copy of the data from the online tape copy. NCEDC disk systems have been upgraded to include 100TB of redundant disk storage.
- *Data backup*: A SL500 tape library purchased and installed, which writes LTO5 tapes. It provides online backup of all data residing at the NCEDC. This purchase, which replaces the old, obsolete tape library, was completely funded by other sources. All SAMFS/ZFS copies have been migrated to the new tape library. All offsite

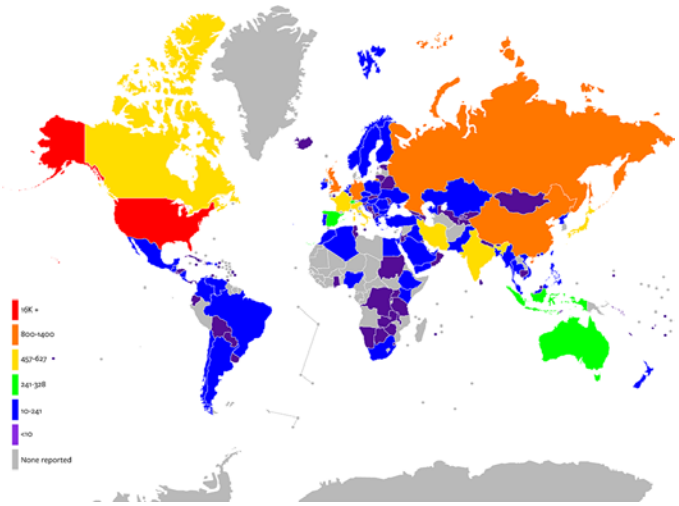

Figure 2: World map of NCEDC data distribution

archival tapes have been re-written to be compatible with the new system.

- *NCEDC data in cache*: This means that data requests are serviced more quickly.
- *Fiber channel switches*: Eight GB fiber channel switches purchased and installed to serve as data conduits between RAIDS and other systems. Fiber cards were upgraded in the data center computers that serve most of the data.
- *Data center database upgrades*: Data center databases were upgraded to Oracle 11, and data center computer operating systems to Linux at UCB (currently still Solaris at USGS MP). Since the configurations of these computers are quite complex, we used "live upgrade" from Oracle to perform the upgrades, and documented the procedure thoroughly. The information is available for others to use.
- *Data Center metrics:* On requeste, we provide waveform completeness reports on request for BK, BP and NC stations to the ANSS since 2012. Average monthly completeness value for the networks we operate are higher than 99%. We now also provide summarys of where NCEDC data is used (Figure 2)
- *ANSS Composite Catalog*: The BSL/NCEDC continues to host and serve the ANSS Composite Catalog, originally created as the CNSS Composite Catalog. This catalog continues to be used by the scientific and public community as a uniform source of earthquake information while ComCat is slowly being developed and populated. We envision the ANSS Composite Catalog to be a critical source of combined ANSS and global earthquake information until the new ANSS Combined Catalog (ComCat) is fully populated with historical information.
- *Completion of Web Services*: We developed and added network services as a means to retrieve data through a web browser (http://service.ncedc.org/) or with web-capable software tools. The NCEDC has fully implemented all of the FDSN-specified web service for delivering earthquake catalog in QuakeML, station/channel information in FDSN station XML format, and time series data in MiniSEED format. In addition, we implemented a number of IRIS-defined extensions to facilitate our web services to better interact with IRIS-provided programming scripts and toolkits. We also defined and implemented an EventData web service that delivers event-based time series data specified by events in the earthquake catalogs hosted at the NCEDC.
- *Web Page Upgrades*: With a great deal of effort on our part, and integrating valuable input from our community of users, we reorganized, modernized and upgraded the NCEDC web pages: http://ncedc.org.
- *Continuous NC data from 1993 to present*: UCB and USGS MP have now archived continuous data from past years from the NC network that was stored on tape. All available continuous data from 1993 – 2005 are now at the NCEDC and available to users. They are already being used in research. Realtime continuous archival of data collected by USGS MP began in 2005 and those data are also available at the NCEDC. The USGS MP is still investigating whether even older tapes of continuous data can be read. If they succeed, we will also archive that data.
- *Archiving PG waveform data (1987-2006)*: PG&E has operated seismic stations in California for many years and determined event parameters. In 2006, PG&E began contributing data from its stations, the PG network, to the USGS MP for inclusion in real time earthquake monitoring. Data since that time are archived at the NCEDC. PG&E had stored "snippets" of data for events between 1987 and 2006. These snippets have now been archived at the NCEDC as "continuous" data. This is the first step to including PG waveforms in existing event gathers from before 2006 when appropriate.
- *Archiving continuous BG data*: At the request of and with funding from a UCB researcher and in cooperation with our colleagues at USGS MP, we are now archiving continuous data from the BG network. The BG stations are equipped with 3-component geophones which are recorded at 500 sps. The continuous waveforms will be used for research into temporal changes in the velocity structure in the Geysers region. They are available through the NCEDC.
- *"Historical" Northern California waveform and parametric data*: Event gathers from before late-November 2006 archived at the NCEDC only included data collected by USGS MP. Since 2006, event gathers include data from all stations collected in real time by either USGS MP or by UCB. Since 2009, we also add data from CI wavepools to the events where appropriate. The NCSS catalog provided to the NCEDC from the NCSN prior to 2006/11/29, was in hypoinverse format, which was a merged catalog of events detected by the NCSN

real-time system and events detected and analyzed by the NCSN CUSP system. The waveforms provided by the NCSN from this time period came from the the CUSP processing system. We discovered that there was not necessarily always a proper mapping between the eventid in the catalog and the CUSP waveform collection for the NCSN event waveform gathers. To rectify this situation we are using the following procedures: For eventids in the catalog that did not have corresponding waveforms (based on eventid matching from the CUSP waveform collection), we determined the appropriate time window for the desired waveform channels for the event, and have collected them from the unassociated CUSP waveform collection and the data from the continuous NCSN event waveforms that have been recently archived at the NCEDC from the continuous waveform tapes created by the NCSN. However, that left a number of events from the NCSN catalog prior to 2006/11/29 for which there were no waveforms. We will again attempt to collect waveforms from the BK and BG networks from the event data added to the NCEDC through the LBNL project for 37769 events collected by the BG network between April 2003 and August 2007. The NCEDC has 81940 CUSP event waveform collections that have no corresponding catalog entry. We created subnet trigger events in the database for a few of these waveform collections so that the USGS/MP staff could analyze them using the jiggle event analysis program. Some of these events are noise triggers without earthquakes, some of them are duplicates of events in the catalog, and some of them are events that were not in the original NCSN catalog. We are waiting for the USGS/MP NCSN staff to determine what action we should take (if any) to handle the remaining unidentified event waveform collections. In the past, as part of the process of bringing online old data and completing the parametric event information available, we have ingested events and waveforms from "old" NC datasets into the database. On reviewing available information, we have discovered a large number of events with no waveforms (although they stem from an era with digital waveforms). We have started the process of generating the most complete waveform collections possible for these events. Two other ongoing projects are the association of waveforms from BK, BP, WR and PG stations with appropriate events in the database, and the replacement of BK and BP waveforms with QC'd data.

3) Seismic station installation, operation and maintenance

Up-to-date information about UCB stations is available through our recently updated station information web pages. Please enjoy the new pages at http://seismo.berkeley.edu/networks. They include station pictures as well as links to metadata. Especially important to our quality control efforts are the figures on the new "data quality" tab. They provide a rapid way to review and evaluation station performance. The new web pages are part of an ongoing effort to modernize and improve the BSL's web presence.

New seismic stations and deployments: During the project period, we added a total of 10 new seismic stations to the BK and BP networks with support from sources other than this project, including Caltrans, funds through the LBNL from the *the America Recovery and Reinvestment Act (ARRA),* and the Moore Foundation-funded TremorScope project (http://earthquakes.berkeley.edu/research/tremorscope.html). PETB and CMAB are two borehole stations in the Bay Area drilled and installed with support from Caltrans (PETB, CMAB). The LBNL ARRA funded stations include three new broadband/strong motion (BB/SM) stations on the LBNL campus, VAK, BL67 and BL88 (BL88 is SM only, due to its proximity to heavily travelled roads and parking lots). The TremorScope project targets non-volcanic tremor and seismicity south of Parkfield. The four surface BB/SM stations (TSCN, THIS, TRAM and TCHL) have been completed and have been sending data to UCB through the USGS microwave for several years. The planned boreholes (TCAS, TSCS, TRAY and TRAM) have been drilled and sensors will be installed this Spring. Each borehole site will be equipped with downhole, three-component geophones which will be digitized at the surface; downhole, three-component BB and SM sensors which will be digitized downhole; and a surface accelerometer. Finally, we "adopted" the former Geoscope station SCZ, in the coast ranges near Salinas, CA. This broadband station, which has been hosted by UC Santa Cruz, has been operating for more than 25 years. It is equipped with STS1s. We replaced the French data logging system with at Q330HR and upgraded the STS1 electronics with a E300 package. We have been collecting data from a co-located STS2 to confirm the instrument response of the STS1. We will soon replace the STS2 with an Episensor purchased by UC Santa Cruz. The station will then satisfy ANSS criteria. Other station-related activities include a demonstration project to show that recordings of tilt can be used in receiver function analysis in the same way as horizontal channels of broadband

seismometers. For this project, we temporarily installed Q330 data loggers and STS-2 broadband seismometers at OXMT and MHDL. Data from all sites flow into the AQMS earthquake information system. Stations still "in the works" include the 4 TremorScope borehole stations, and an installation of BB/SM equipment from LBNL in the Lawson Adit on the UC Berkeley Campus. Its name will be ADIT. The required power and telemetry preparatory work has been completed, and we will install the equipment soon.

Equipment Upgrades: The past five years have seen extensive upgrades to the equipment at the BK and BP seismic sites. The principle source of that equipment was the USGS, through the ARRA. ARRA government furnished equipment (GFE) included data loggers (Q330HR) for 25 BK BB/SM stations, 10 Episensors to replace FBA23s at BB/SM stations, and 22 data loggers (Basalt) for borehole sites (BK and BP), where we sample at data rates of 250 or 500 sps. All the equipment were installed under the ARRA project, except for two Basalts which were intended to be installed at CMSB (the borehole near the Cal Memorial Stadium) and at RMNB in Parkfield. Shortly after the beginning of the ARRA project, the Memorial Stadium retrofit and renovation began and CMSB was shut down. At the end of the project, the borehole was "lost" with all the downhole equipment in place. Its replacement was finally completed about a year ago, and the University has purchased new equipment to replace the "lost" equipment. That equipment will be installed soon. We no longer have an agreement with the landowner for RMNB, so may no longer access the site. Having the "spare" Basalts has been useful, as we troubleshoot their soft- and hardware configurations and are thus able to rapidly replace/upgrade systems during a single trip, rather than having to retrieve the data logger, reconfigure and then replace it in a second site visit. For a report on the ARRA upgrade activities see http://earthquake.usgs.gov/research/external/reports/G09AC00487.pdf.

A second round of upgrades occurred at the Bay Area borehole/strain sites OXMT, SBRN, MHDL and OHLN. There, the GFE Basalts were replaced with GFE Q330s to allow collection of tilt, strain and pore pressure data, as UCB "adopted" the maintenance and collection of this additional data from these deformation monitoring stations.

In addition to the ARRA upgrades, we have been able to find funds from other sources (Caltrans, Federal Emergency Management Agency (FEMA) through the California Office of Emergency Services (CalOES), and Incorporated Research Institutions in Seismology (IRIS)) to replace all our "old" data loggers except one, to replace the sensor electronics at all but three of our 10 stations operating STS1s and to replace long run cables (55 ft and 120 ft) between data loggers and sensors at two of our sites (YBH and KCC). With the ARRA upgrade, we lost the capability to digitize data from the STS2 for nuclear monitoring at YBH. We received a new data logger for that to digitize data from that sensor from AFTAC.

Seismic network operation and maintenance: In the past USGS funds contributed primarily toward the operation of UCB's borehole stations in Parkfield and the San Francisco Bay Area under separate projects. As the projects have now been merged under this cooperative agreement, and much of the equipment throughout the UCB networks is GFE, we have increasingly used funds from this project for station operations (primarily telemetry costs) and maintenance contribute to supporting activities at all our stations. An important activity that began during the project interval and is continuing, is a test and evaluation of the E300 replacement electronics for the STS1. We have noticed "instrument response changes" over time on several STS1 components, particularly the E component of the STS1s at YBH. Currently, BK BB/SM stations KCC and BRIB are off-line. It is difficult to reach KCC during the winter due to snow. We hope to resolve the telemetry problems there soon. The tank at BRIB was flooded in a very heavy December 2014 storm. BRIB has been down since then. We retrieved all the equipment from the tank in January and pumped it out. We are developing a plan to replace the tank, which has flooded several times, with an above-ground hut. XXX - Bob's info

HRSN operation and maintenance: In addition to the data logger upgrades at the HRSN, the ARRA and this project have funded maintenance tasks to improve the reliability of station and network operation. Field activities included cleaning and replacing corroded electrical connections; grounding adjustments; cleaning and replacement of solar panels; re-seating, resoldering, and replacing faulty pre-amp circuit cards; testing and replacing failing batteries; and insulating and painting battery and data logger housings to address problems with low power during cold weather. During the past two years, we have developed, produced and installed new preamp electronics for all the HRSN stations. Their installation has alleviated many, but not all of the noise problems. During the ARRA upgrades and since, we have discovered a number of problems with the Basalts. The "teething" problems, discovered and mostly alleviated with the help of Kinemetrics as we installing Basalts during the ARRA (see http://earthquake.usgs.gov/research/external/reports/G09AC00487.pdf). Other, more recently encountered

difficulties include repeated reboots. These have 2 different sources. The first is because Kinemetrics provides two cable sets for the Basalt, one for "permanently powered" systems, and a separate cable harness for solar/battery powered systems. Under the ARRA, we had received and installed the former, when clearly the latter would have provided better performance. We are in the process of replacing the cable harnesses at all Basalt sites with those meant for battery powered systems. The second source of problems is that the 16GB CF cards, which record the data and also have the operating system, were not as "industrial" as expected. They have begun to perform poorly due to heat and many rewrites of the FAT. Kinemetrics has supplied higher quality CF cards, and we are swapping them in at the stations as quickly as possible (both at Parkfield and in the Bay Area).

We reconfigured the telemetry at Parkfield to reduce load on the radio link between Carr Hill and the fire station. This link was degrading, as trees occluded the antennas. The degradation became critical a few years ago. Working with USGS MP colleagues, we were able to reduce the traffic on the radio link by a factor of three. The HRSN computer is now installed at Carr Hill, and only data from stations coming directly into the fire station use it.

The HRSN stations continue to contribute important data for both observing seismicity in the Parkfield area and studying the non-volcanic tremor at the transition from the creeping to the locked section of the San Andreas Fault. Bob Nadeau presented a summary of earthquake monitoring and research based on HRSN data at a recent NEPEC meeting in Menlo Park.

NHFN operation and maintenance: During this project, routine maintenance has been performed at the stations, and we continue to try to improve operations, and data collection and quality control. Shortly after the ARRA data logger upgrade, construction at the school hosting station OHLN disconnected power and telemetry there. This site finally returned to service in the week before the South Napa Earthquake, which was recorded well. We completed the adoption of maintenance and operation of the strain, tilt and porepressure equipment at the stations OXMT, MHDL, OHLN and SBRN. For this purpose, we received and installed GFE Q330 data loggers from the ANSS Depot which replace the ARRA Basalts. Colleages at USGS Menlo Park provided QEP units (Quanterra Environmental Packages) that add 3 additional 24-bit digitizer channels to the Q330. The geophone and strain channels are digitized on the main unit; the channels on the QEP are used for pressure and tilt. Quanterra data loggers were supposed to be able to communicate with the serial porepressure devices, but the firmware of the permanently installed porepressure sensors cannot be upgraded and it is too old to work with the Q330. Sadly, during the very heavy rain in December 2014, the equipment tank at our station BRIB was flooded (~4 ft deep in water), not for the first time. The Episensor accelerometer in the tank succumbed to the water influx. Other recovered equipment appears to be working. The tank was pumped out, but "took on" about 5 further inches of water during subsequent storms. We are developing plans to replace the tank with an above-ground hut to house batteries, data loggers and telemetry support equipment and hope to have the station back on-line during the summer.

Telemetry Improvements and Conversions

Since we have been informed by AT&T that frame relay, which provides telemetry for many of our stations, will be deprecated, we have been exploring alternatives and transitioning stations to other telemetry options. We have begun the transition away from frame relay, replacing that service with "host internet", where possible, and cellular modem services, primarily from Verizon. During 2015, we will continue the transition process. We expect that this transition will reduce expenses, as the cellular modem services cost less than frame relay. About twenty of the geophysical stations that UCB operates -- these include our GPS-only sites -- remain to be transitioned.

4) Earthquake information production and improvements

ShakeMap Operations: We transitioned to using ShakeMap 3.5 in production in June 2011, and at the same time, implemented the use of PDL for transporting NC ShakeMap products to the servers in Golden. UCB was the first network operator to do so, and Pete Lombard provided to support to other networks as they make the same transition. He has also been an important source of feedback to the ShakeMap team on bugs and improvements to the package. In the NCEMC, we will eventually recalculate maps for all old events for two reasons. First, ShakeMap3.5 (and now the latest version) provides new elements of the product which are important for their display. Second, for a number of past events, the catalog ID and ShakeMap ID do not match. We are now waiting on two efforts, a decision about the best GMICE, and the implementation of the new depth datum (so that new maps will have hypocenters consistent with the catalog). As part of the preparation, we reviewed the aftershocks of

the 2003 San Simeon earthquake, many of them small, for which ShakeMaps had been calculated. We revised magnitudes of many of them, and also raised the "ShakeMap" limit upward from 3.5 to 4.0 for the 6 months following the mainshock. To ensure that all events have the full complement of ground motion information, we also harvested the ground motion values from the old ShakeMap database and entered them into the AQMS database in association with the correct events. We have adopted the new VS30 map and a broader area topography bitmap, so that large events with affects outside of our reporting area will still be represented well. Peggy Hellweg chairs the CISN ShakeMap working group, which coordinates ShakeMap activities in California. Bordering regional, like PNSN and NN have designated members of the working group, who participate when needed. During this project, CISN agreed that California Geological Survey (CGS) will provide ShakeMap backup for the NCSS and SCSN. The CGS ShakeMap production system is now operational and working well. To do this, they now receive PDL feeds of earthquake information from NEIC, ATWC and PTWC to trigger the operation of their system. They also listen to ensure that they only publish ShakeMaps in PDL when the authoritative network has not published a timely map. During this project, we updated the Northern California scenario ShakeMaps were recalculated, to match the UCERF faults scenarios (http://www.cisn.org/shakemap/nc/shake/archive/scenario.html). They are also available through the USGS ShakeMap webpages. With help from colleagues at CGS and USGS Menlo Park, we have updated the Parkfield ShakeMap to include updated ground motion values (http://www1.cisn.org/shakemap/nc/shake/51147892/intensity.html.

Regional moment tensor software package: We have continued to improve the realtime regional moment tensor software package and its review interface. Now, full moment tensors can be calculated during review, that is moment tensors may be produced, published and stored which include an isotropic element. All "old" Geysers events (back to 1995) were reviewed to determine deviatoric solutions and were then evaluated in terms of possible isotropic elements. We working toward allowing the use of data from strong motion sensors in the moment tensor interface. In addition to these developments, we have improved robustness of our moment tensor calculations by operating the moment tensor review interface on two servers which access different databases. We have also developed and implemented code that allows the moment tensor interface to request "historical" data from IRIS data servers.

Data and parameter exchange with the Southern California Seismic Network (SCSN): In the Spring 2010, we implemented wavepools for exchanging event waveform data with the SCSN. SCSN now requests Northern California waveforms for its event gathers, and the NCEMC requests Southern California waveforms for its event gathers. In the meantime, realtime exchange of waveforms for picking, ground motion parameters and local magnitude determination has improved, with Northern California accessing data from CI stations within 100 km of our mutual boundary.

We have been testing the use of remotely determined picks for several years. Toward the end of the project, we began the process of officially exchanging picks, and are discussing the exchange of other parameters. These activities improve event characterization and magnitude estimation for large events, and for those near the network reporting borders.

Implementation of real-time double difference (DD) event locations: Double difference earthquake locations give a more focused view of faults and seismic sources. We are working with USGS MP on the implemenation of DD processing within the AQMS system. After an event has been located with hyponiverse, a DD location will automatically be determined and stored in the AQMS database. We have participated in the development of suitable schema and the implementation of processing proceedures. Now that decisions have been made and implemented regarding the storage of DD-RT related information in the AQMS database, DD-RT on in production in the NCSS.

New ANSS depth datum standards: During the past 2 years, the ANSS developed a policy that earthquake depth shall be reported with respect to the geoid. Hypoinverse, as implemented in the NCSS determines depth relative to the surface of the velocity model - which is approximately the average elevation of the nearest stations. Following extensive discussions in the NCSS and through the CISN Standards and Schema Change Working Groups with our Southern California partners, we have revised the AQMS/CISN schema to support storing both the geoid depth (depth) and the model depth (currently provided by hypoinverse). Fred Klein has modified hypoinverse to now provide both model depth and the average elevation of the nearest 5 stations, and Allan Walter has implemented a procedure that calculates the average elevation of the nearest five stations, based on information in the database. We have been testing these procedures and exploring the events where they do not appear to work well. We are

close to implementing the new depth datum for both historic NCSS earthquakes, and going forward. When the implementation is complete, we will submit the NC historic catalog to ComCat.
Earthquake Response and Reporting: We have made an improvements to earthquake reporting and response capabilities. At the request of our colleages at NEIC, we have implemented a single "call-forwarding" number. This number will be forwarded to the cell phone of the UCB duty seismologist.

4) *Metadata review, updates and improvements*: We have been reviewing metadata for all the stations for which we collect data in the NCEDC, and which we use in realtime operations. These include data from the BK, BP, BG, PB, PG, WR, NC and NN stations. In particular, several questions have cropped up about, (a) channel polarities for use in first motion mechanisms, (b) orientations for horizontal sensors, and (c) sensor sensitivities over time. We also worked with our colleages from the NCSN to review instrument response information for the STS-2 stations they operate.
(a) Channel Polarity: We developed a procedure to extract information on stations with reversed polarities from the database, obviating the need to manually keep and update a "reversed polarities" file. We then proceeded to evaluate the polarities of all stations, in particular however, the vertical components at the borehole and geophone sites throughout the region, including those from PBO boreholes. We updated the metadata to reflect the results, and now harvest updated polarity information for fault plane solutions from the database. We have provided information on polarities to PBO.
(b) Channel Orientation: Particularly for borehole sensors, the orientations of the horizontal channels is not always clear. Taka Taira has developed procedures to use P-waves from local earthquakes and (deep) teleseisms to evaluate the orientations. The new/corrected orientations are submitted to the database. He has participated in a project with UNAVCO to document the orientations of the geophones in the PBO boreholes.
(c) Sensor Sensitivities: Taka Taira has developed procedures to compare data from two co-located instruments, such as a broadband and strong motion sensor at a given site, to determine whether the instrument response of two channels with the same orientation agree. In addition to a waveform comparison, he shows spectral amplitude ratios and phase differences. If the former is about 1 and the latter about zero, instruments information is correct and instruments are working properly. In a second step, he collects data over time from a suite of earthquakes to verify that sensor parameters have not changed. We regularly use these procedures to evaluate all stations in the BK and BP networks where equipment is co-located. We proposed to USGS MP, that Taka could apply these same techniques to the NC stations with co-located short period (SP), vertical seismometers and accelerometers. We discovered that while the sensitivity of the SP seismometers at most NC stations is consistent over time, there were quite a number of stations where this was not true. At some locations, the actual sensitivity appeared to be about 20% of what it should have been. We have been working with the USGS MP team to update and validate the instrument response for the sites with inconsistent parameters, while Fred Klein also sleuths in station records to determine dates and causes of sensitivity changes. When this task is completed, we will review the sensitivities of the SP-only stations using deep teleseisms.
In addition, we have been working on improving calibration and calibration procedures for our STS2 seismometers. This was initiated by the CTBT requirement for annual calibration of their sensors. We discovered that (a) it is difficult to perform a full calibration of an STS2 if the Q330 data logger only has three channels, (b) the information about the calibration coil of the STS2s is not precise enough, and (c) for the high-gain STS2s, the "background" seismic noise at even a very quiet site can affect the results. In the near future, we will calibrate all our STS2s to determine the variation in the calibration coils as input for improving procedures. The results, procedures and tools will be available for general use.

5) Participation and Support for AQMS: UCB personnel have participated actively in supporting the rollout of AQMS to other networks. We prepared and gave many presentations on AQMS operations and details at the Net Ops workshop in February 2011 in Pasadena. We have answered many email questions as other network operators have implemented their systems. And we sent our database manager to University of Utah to support and train the folks there.
July 2011 Network Operators meeting: UCB hosted a meeting of the ANSS Network Operators in July 21-22, 2011. At this coordination meeting several committees received charges, to (a) advise the development of the

Comprehensive Catalog, (b) review requirements for implementing a system for instrument tracking and metadata, and (c) review the status of Class C instrumentation and develop the requirements under which data from such instruments can be used in realtime operations.

March 2012 NetOpsVI meeting: In March, UCB hosted NetOps VI. This meeting was dedicated to field/engineering personnel. More than 50 people from most ANSS networks attended, including several people from Albequerque Seismo Lab's field team, who introduced the equipment depot and procedures. The meeting was very productive for all participants (see http://www.ceri.memphis.edu/people/mwithers/NetOpsVI/).

UCB participation in ANSS/CISN committees:

National Implementation Committee: Peggy Hellweg, Doug Neuhauser. SIS Technical Implementation Committee:

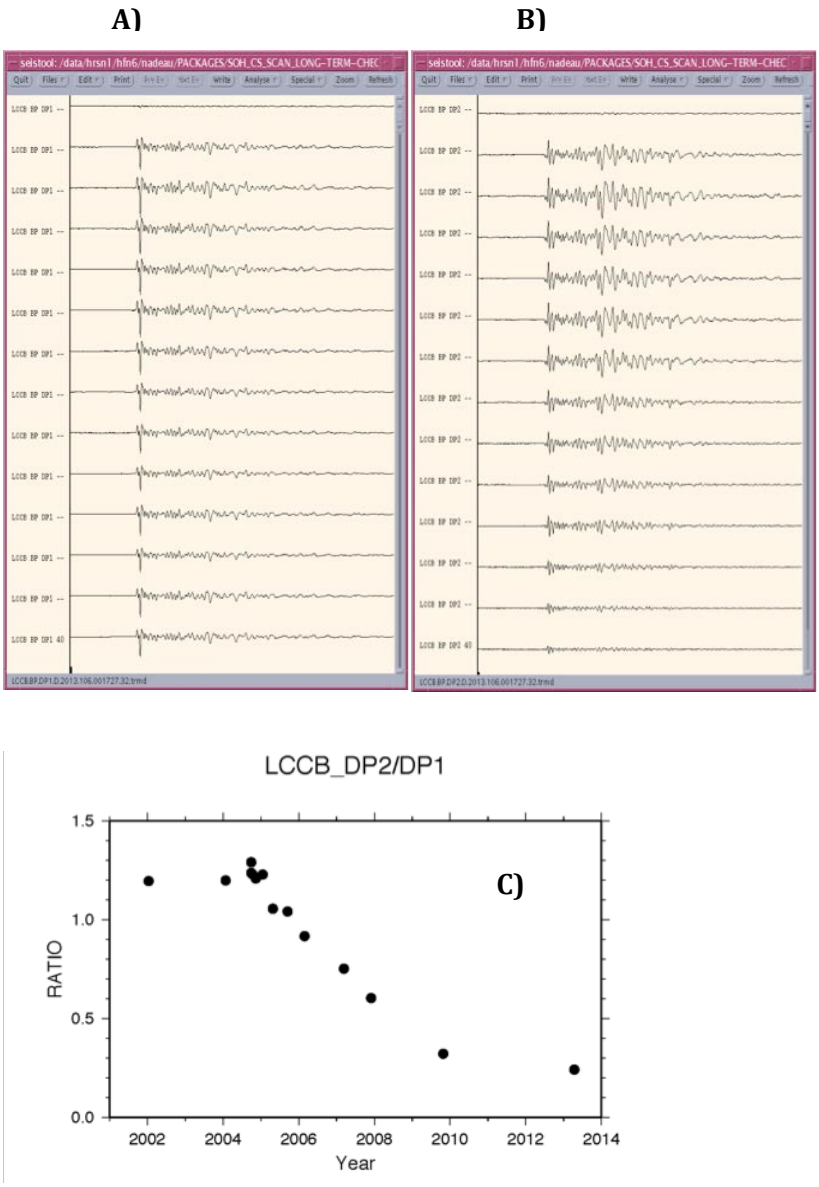

Figure 3: We have been using repeating earthquakes to evaluate channel sensitivities over time for UCB stations in the Parkfield area. Signals from repeating events are used to evaluate channels through time. Performance that can be evaluated, include outages, noise levels, time-tears, inadvertent polarity flips and channel swaps, problems that evolve over time. (A and B) Absolute scaled raw velocity seismograms of 14 repeating earthquakes occurring from 2002 to 2013 as recorded by HRSN channels DP1 and DP2, respectively, at station LCCB are shown. Top trace is from the 2002 event, before an instrumental gain increase of x12.5 was applied to the pre-amplifier unit on Nov. 3 of 2003. Waveforms and amplitudes recorded on the DP1 channel remain stable throughout this period. In contrast, the DP2 channel shows a progressive decrease in amplitude over time. (C) shows the ratio of the peak values of the DP2 to DP1 channels over time. This ratio compensates for modest differences in the magnitude of the different events in the repeating sequence. It is apparent that the strong decrease in DP2 starts in late 2005. Despite the amplitude decrease, the waveform shapes appeared to be unaffected and maximum cross-correlation values among event pairs remains relatively high. However, inspection of the spectra (not sown) shows that the decreasing DP2 amplitudes are primarily the result of a decrease in the lower-frequency energy on DP2. Investigation into the cause and solution for this problem are current action items.

Doug Neuhauser, Stephane Zuzlevski. Class C Working Group: Peggy Hellweg (chair). Depth Datum Working Group: Peggy Hellweg. ComCat Working Group: Peggy Hellweg (alternate Doug Neuhauser).

As other regional networks have begun to use AQMS, the CISN committees for coordinating and improving operations are open to include members from those networks, to discuss problems, questions and improvements. The CISN Standards Committee (chair Doug Neuhauser) provides overall technical coordination. The CISN

Schema Change Working Group (chair Stephane Zuzlevski) evaluates and coordinates the implementation of changes to the AQMS schema. The CISN ShakeMap Working Group (chair Peggy Hellweg) discusses ShakeMap operations in the regional network(s). Other working groups in CISN include: Data Exchange Working Group (to exchange data between regional networks and strong motion users), Magnitude Working Group (chair Peggy Hellweg; to develop and improve local magnitude estimation). UCB staff members contributing to these groups include Stephane Zuzlevski, Taka Taira, Doug Neuhauser, Pete Lombard and Peggy Hellweg.

6) Other topics

Implementing Earthquake Early Warning: We continue to make improvements to our operational systems to support earthquake early warning (EEW) processing. One result of the ARRA data logger upgrades is that data from UCB stations equipped broadband and strong motion sensors is delivered to the data center in 1 s packets. Doug Neuhauser made improvements to *qmaserv* to allow the 1 s packets to be distributed immediately and the data in them made available for EEW (and other) processing. This is in contrast to previous processing, in which data from the 1 s packets were reaggregated to miniSEED blocks containing 4-8 s of data. The use of 1 s packets provides a considerable reduction in data latency, thanks to the ARRA upgrades. We moved EEW waveform processing from the research computer systems to the more robust operations computers at UCB and USGS MP. This is an early step toward a more fully operational EEW system. UCB participants led the project to evaluate uncertainties in the EEW event estimates. All algorithms now contribute these parameters to the Decision Module. We prepared and provided to our colleagues a proposal for the structure for a robust, redundant EEW operational system, which is now the template for implementing the protoype EEW production system. UCB's Doug Neuhauser is chair of the Production Prototype Implemenation working group. We also prepared and shared with the EEW project members, on-line gui-EEW evaluation tools. At the UCB, we are making good progress toward integrating GPS into the EEW processing. Our algorithms ElarmS has provided EEW alerts within 4-5 s for events in the well instrumented areas of California, and GlarmS performed well in the South Napa earthquake.

GridMT, scanning RT data for big earthquakes: With funding from the USGS through the NC NEHRP program, UCB has developed a scanning program to detect and characterize earthquakes up to M9. The primary application region for this process is offshore of Northern California and Cascadia. Data from up to four stations is used to detect whether an earthquake is occurring and determine its approximate location (on a grid), its mechanism and its magnitude. It has successfully detected quakes offshore of Northern California with M~4-5. It was also applied to data from Tohoku with great success. The scanning algorithm is running on the real-time data streams from the stations HUMO, YBH, WDC and ORV. We are also coordinating with partners from the Pacific Northwest Seismic Network to incorporate data from one or more of their seismic stations, to improve estimates for Cascadia earthquakes affecting more northerly regions. GridMT now regularly reports on events off-shore of Northern California and Southern Oregon, some even that have not been detected by the realtime AQMS system.

Scanning old seismograms: UCB has a huge collection of seismograms dating back to 1910. We have had requests for copies/scans of pre-digital events such as the Fairweather quake of 1958 and the Queen Charlotte Island of 1949. The data are being used to investigate these old earthquakes and compare them with more recent events. We recently purchased a new, high-quality scanner and computer, so that we will be able to produce good digital version of the paper records.