

**Final Report for the 2015 – 2020 USGS Cooperative Agreement for Seismic Network Operations
Cooperative Agreement Number: G15AC00042**

***Operation of the Northern California Earthquake Management Center, and the UC Berkeley Seismic
Networks: Feb 1 2015 – Jan 31 2020***

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Abstract

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 Seismic System (NCSS). The NCSS effort is a joint operation of the USGS Menlo Park (USGS MP) and UCB. 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 NCSS. UCB operates the system of digital geophysical stations with broadband and strong motion sensors comprising the Berkeley Digital Seismic Network (BDSN; network code BK). In addition, operating support to UCB for borehole seismic networks in Northern California has been folded into the current agreement. These networks are the High Resolution Seismic Network in Parkfield (HRSN; network code BP) and the Northern Hayward Fault Network in the Bay Area (NHFN, which includes some miniPBO sites; included in network code BK). Data from all borehole sites have been contributing to real time earthquake monitoring since before the transition to AQMS software in June 2009. As always, such a project faces challenges successes. During the past five years, the challenges have taken the form of staff turnover, technical problems with instrumentation and telemetry, and problems caused by nature: flooding, fires, etc. Our great success, aside from the regular operation of the earthquake information system and the collection of high quality data for monitoring and research, is the addition of more than 40 broadband/strong motion stations to our network to improve speed and quality of detection of earthquakes in our region for earthquake early warning, and the expectation of adding at least 60 more in the coming years.

Introduction

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 Seismic System (NCSS). The NCSS effort is a joint operation of the USGS Menlo Park (USGS MP) and UCB. 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 NCSS. UCB operates the system of digital geophysical stations with broadband and strong motion sensors comprising the Berkeley Digital Seismic Network (BDSN; network code BK). In addition, operating

support to UCB for borehole seismic networks in Northern California has been folded into the current agreement. These networks are the High Resolution Seismic Network in Parkfield (HRSN; network code BP) and the Northern Hayward Fault Network in the Bay Area (NHFN, which includes some miniPBO sites; included in network code BK). Data from all borehole sites have been contributing to real time earthquake monitoring since before the transition to AQMS software in June 2009.

This project interval has seen extensive turnover in staffing: we "lost" and had to replace our entire field engineering staff, with essentially no overlap to pass on knowledge about our field operations; Doug Neuhauser, UCB's original data center manager, retired after ~27 years; and Pete Lombard, our AQMS programmer and operator, also retired. We are fortunate that Doug Neuhauser has been "recalled" and continues to provide insights, advice and programming for applications that he developed and a historical view of the network operations. Pete Lombard has been working on the catalog integration project (see below), and also answers questions when we run into an "information deadend" in areas of his expertise.

Other big impacts and projects during the past 5 years include: the transition away from frame relay, mostly to cell modems (except for GASB, which continues to record but has no telemetry; data are retrieved occasionally by "sneakernet"); the impact of the environment on our stations, including exceptionally rainy years which flooded sites (HELL, BRIB) and recent great fires such as the Carr fire (WDC); the aging of the seismic sensors and equipment in both the BDSN and HRSN; the collaborative effort to improve and merge the Northern California catalogs which cover the years from 1932 to the present; the need to move away from Oracle and the activities toward that goal; and the biggest project, the implementation and operation of the West Coast ShakeAlert earthquake early warning system, and the associated growth of the BDSN as part of the buildout. In 2015 when this project began, we operated 63 seismic stations (including borehole and surface sites), we are now operating almost 130 and are expecting to install and operate seismic monitoring equipment at 60 additional sites in the next two years.

The narrative below describes the challenges, activities, achievements and more from the past five years.

1) *Operation, improvement, fine tuning and software support for the ANSS Quake Monitoring System (AQMS) software for Northern California.* Since June 2009, the AQMS software for monitoring earthquakes and publishing earthquake information has been operating in Northern California. Until recently, UCB personnel provided 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. UCB staff operates, maintains and upgrades the Oracle databases which are fundamental to the operation of AQMS, and the NCEDC data center. In the NCSS, two parallel systems operate continuously, one in Menlo Park and a second at UCB, each system having one real time 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 at each location. The datacenter databases replicate with each other and with the public database (which resides at UCB), to ensure that information is always up-to-date in all databases. The public database provides information to the public. Information about activities toward transitioning the database from Oracle to Postgres is also described below. We continue to improve and fine tune the parameters of the AQMS system, regularly upgrading software, operating systems and the database to include patches. When David Oppenheimer retired, Dr. Lind Gee requested an "AQMS Tutorial" for herself and other new members of the USGS MP staff. This was provided by Pete Lombard during several visits to Menlo Park. This work contributes to the robustness of our joint earthquake information system. When the USGS MP is "off line" due to government shutdown as happened in late 2018 and early 2019, UCB takes over all operation, including earthquake reporting and response.

Developments and improvements we have made to the AQMS processing system over the past five years include the following.

1.1. *Implementing Comprehensive Catalog (ComCat) and Product Data Layer (PDL) for publishing all earthquake products and the historical catalog to Golden:* We have worked with the team in Golden to implement and fine tune PDL for transporting all earthquake information products produced in Northern California (and at other centers operating AQMS) into the ComCat system. We submitted the NCSS historic catalog to the ComCat through PDL, including all existing products for each event within our reporting boundaries since the early 1970s. This took several months and was completed in early 2017. Our decision

to submit only events from within our reporting boundaries was based in part on the fact that neighboring networks had already submitted poorly constrained events in our reporting area; we did not want to exacerbate the problem ComCat has with such events. The extensive “clean up” of the NCSS catalog included implementing the geoid as the reference for earthquake depths (see 1.2), deciding on the region and types of events to submit, and developing a means of tracking which events and products were submitted to PDL. Regarding the latter, tables for tracking submission were proposed to the CISN Schema Change Working Group, and tools were implemented to use them. The preparation for submitting the historic catalog to ComCat brought on a discussion of what the NCSS should be submitting to the current EQs web pages and to ComCat. In real time, only events within our reporting boundary are submitted; after being reviewed, all events are submitted. The NCSS continues to submit event information and products to (ComCat) using the Product Distribution Layer (PDL), and provides timely feedback to the EHZ development team on both PDL and QuakeML issues.

1.2. *Depth Datum, Historical Catalog and Event Labels:* During this project, as part of the major effort of submitting the Northern California (NC) historical catalog to ComCat, the NC catalog was converted to reporting earthquake depth in reference to the the geoid. Shortly after Thanksgiving 2016, we began submitting the Northern California historical event catalog into ComCat. Initially, about ~950 events were submitted per hour, however as the number of products associated with an individual event increased over time, the submission rate dropped. The catalog submission finally completed in mid-February, 2017. A number of steps were completed by UCB and USGS MP staff before we began submission. The results of a "catalog review" script provided by NEIC showed a number of inconsistencies in the NC catalog (Table 1), or inconsistencies with information already in ComCat. The inconsistencies were either resolved, or adjudged unimportant.

Table 1: Preparation for submitting the NC Catalog to ComCat

Catalog Problem	Description	Resolution
700 events with Mh=0	Mh indicates that the event has a "hand" or "human" magnitude, they should have had values.	These events were all reviewed by Hal Macbeth.
unknown number of events with no/ corrupted waveforms	These events could not be reviewed, as no, corrupted or incorrect waveforms were associated with them.	Where possible, waveforms will be recollected from the continuous waveform archive. We are reviewing all event gathers in the NCEDC for waveform corruption and have found between a few and ~50 per year.
Magnitudes for large events	Magnitudes in the NC catalog for events with M>6 may not be consistent with their "official" or accepted magnitudes.	We reviewed these cases and decided to submit the events as they are.
Unmatched events in our authoritative region	During the catalog review process, many small events were noted in the Sierra Nevada for recent years (>2010).	These are tiny events reported by NN in our authoritative region, where they have seismic stations, but NC and BK networks are sparse.
Magnitude/location differences between NC catalog info and other reports of events in our authoritative region	CI and NN submission to ComCat included events in the NC authoritative region.	The submission of events from the NC catalog will provide authoritative location and magnitude information to ComCat.

Two important steps had to be completed before we could submit the historic catalog to AQMS: decide on the region and types of events and develop a means of tracking which events and products have been submitted to PDL. Regarding the latter, we proposed tables for tracking submission to the CISN Schema Change Working Group. The schema change was accepted in early 2016 and Pete Lombard implemented tools to use the new tables shortly thereafter. For each event that satisfied the following criteria we submitted ALL available products except ShakeMap:

- Event origin time Since Jan 1 1984 (essentially to present)
- Event location Within current NC authoritative reporting region
- Event magnitude Any magnitude (type and size, including events with no magnitudes)
- Event type All event types except thunder, and sonic booms
- Event products Origin, phase, place name, focal mechanism, moment tensor

The initial NCSS submission starts with events from 1984 to the present, because of the known problems with the NC catalog for earlier dates. There are many events that do not satisfy these criteria, and we are working toward submitting them, too. This is why it is important for us to track which products have been submitted to ComCat.

After the submission was completed, a team from USGS MP and UCB including the retired USGS MP staff members David Oppenheimer and Fred Klein, and retired UCB staff member Pete Lombard started work to resolve the known problems in the NC catalog from before 1984, and to merge the NC and BK catalogs from 1966 - 2003, as well as to QC and adopt the BK catalog from 1932 through 1966. This slow, but ongoing process again demonstrated that there are some problem events in the catalog, which have been resolved where possible. When the process is complete, we will submit/resubmit the affected events – there are many of them. The work includes efforts by Fred Klein and Adria McLean at USGS MP to recalibrate station coda corrections for the entire era of the NC catalog, and to correct M_{ds} , especially for early events. It is likely that we will also recalculate local magnitudes where possible (M_L). The NC-BK catalog merge for 1966-2003 has been completed, and the coda corrections have been prepared. While we develop procedures for entering this revised information into the AQMS database, we are supporting Dave Oppenheimer's processing and QC of the BK catalog. As always, there are some stumbling blocks -- for example, for the sparse network in California before 1966, event locations are produced with very few and sometimes very distant seismic stations. We had to define a process for entering this information into the database, so that were the catalog including these events to be relocated, the new location would not differ from the current location, at least not by much. This work is slow but nearly complete. The next step will be to enter all the updated events into the database and resubmit them to Comcat. Very likely, these submissions will include data and parameters for early nuclear explosions and other regional events of interest that were not included in our initial submission of the historical catalog. In the NCSS, we are continuing the discussion of what we should be submitting to the current EQs web pages and what should (or should not) appear only in ComCat.

Following the initial submission to the historical catalog to ComCat, all available ShakeMaps were submitted in a separate process. This is important because in the past, the realtime and database event IDs were not the same. The ShakeMaps were resubmitted "up to the present", in order to bring them uptodate with the current software, display and product options.

As a by-product of the catalog curation process, we have discovered other problems with the data center, such as bad (garbled) waveforms in event gathers. It is not always clear how these waveforms are garbled and why it happened. We are in the process of investigating how to fix them.

1.3 *Support for AQMS:* UCB personnel have participated actively in supporting the implementation of AQMS by other networks. We continue to answer questions by email or phone as other network operators implement and configure their systems. Members of other networks are encouraged to participate in CISON working groups (e.g., Standards, Schema Change) to contribute to improving AQMS. Staffmembers participated in the ANSS sponsored NetOps workshop on AQMS at the University of Washington in March, 2018.

1.4 *AQMS under Linux:* UCB staff developed a version of AQMS that runs under linux. Since then, all AQMS and data center computers operating in Northern California were migrated to the linux operating system, with the exception of the Double Difference and ShakeMap computers in Menlo Park. Initially, UCB provided extensive support to USGS MP for the migration of the AQMS computers there to linux. In particular, Stephen Thompson used kickstart to remotely installed linux on the machines, and Pete Lombard installed many of the software packages required to support the AQMS software system.

1.5 *Station Information System and StationXML:* The BSL continues to contribute to the discussions, development and implementation of the Station Information System (SIS) hosted by Caltech. Exchange of station and channel information between AQMS and SIS is accomplished via StationXML and extended StationXML. Recently, due to reports from IRIS that the NCEDC's dataless SEED have erroneous parameters, UCB has been providing metadata in StationXML format. UCB developed and implemented the "AQMS-to-StationXML" writer and "StationXML-to-AQMS" interpreter that are used in conjunction with the "StationXML-to-SIS" reader and "SIS-to-StationXML" writer. Without both sides of the system, SIS would be useless to regional networks as a centralized station and metadata system. At the request of the NCSS, the SIS folks have implemented capability in SIS to gracefully handle metadata for "multi-site" stations, such as the Earthworm hubs which digitize data from a number stations with analog telemetry, and other tools to handle the often complex information available for BK stations. Stephane Zuzlevski continues to test SIS

as upgrades are completed. UCB and USGS MP are currently using SIS for new stations that are being installed using EEW funding. We continue to test SIS capabilities; when a few remaining inconsistencies in metadata at BK and BP stations are cleared up, UCB will be able to enter the metadata from our existing station into SIS, too. We are working with USGS MP to develop a plan to migrate metadata for existing stations from the "Fredsheet" to SIS.

1.6 *Oracle vs. PostgreSQL:* Although Oracle provides the foundation for AQMS, particularly in Northern California, where replication occurs across the Bay, it is becoming unusable for 2 reasons. First is the cost to networks which do not have a site license, which UCB does. The second reason to search for alternatives is the requirement for full replication, which will soon become unavailable through the regular Oracle license. University of Washington (UW) invested in the implementation of AQMS database services through PostgreSQL, but without investigating replication. In Northern California, there are normally five databases in operation. The data processing systems on both sides of the Bay each have a real-time database and a post-processing/data center database working at all times (except when operating systems or software are being patched and upgraded). The real-time database is a pared down system that interacts with processing packages that detect and report earthquakes, and determine magnitudes. In most cases, event information is replicated to the local post-processing/data center database (although other options exist and have been used). Each of the data center databases is a "master" database and replicates with its partner across the Bay, and with the public database at UCB. In principle, other configurations are possible, but not as robust. Over the past two years, we have had discussions in the CISN about our options for transitioning away from Oracle and multi-master replication to use the PostGres AQMS system. In concert with Caltech, UCB implemented a pair of PostgreSQL AQMS databases to test full multi-master replication. One option is to use an add-on to PostgreSQL. A second is to adopt a model more like that of the University of Washington. Over the past year and with the help of ISTI, we have begun to set up a test the UW model. on computers at UCB. Progress has been slow, as all staff involved, including those at ISTI have been sidetracked by other, more urgent tasks. In the meantime, the deadline for an Oracle database transition has fortunately been extended. We hope to resume progress on this important project very soon.

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 (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), and 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 Lawrence Berkeley National Laboratory (LBL). Data holdings now consist of more than 140 terabytes of data. The Oracle public database providing data on Northern California earthquakes, part of AQMS, also 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. Data are available now primarily through network services for metadata, waveforms, event gathers and catalog information (<http://service.ncedc.org/>); other options have been deprecated as they are no longer supported. Full waveforms are available as soon as they arrive at the data center through the DART feed (Data Available in Real Time). Improvements and changes at the NCEDC are described below; others, such as improvements to the catalog, are described in other sections of this report.

2.1 *ANSS Composite Catalog:* The BSL/NCEDC continues to host the "original" ANSS Composite Catalog, first 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 being developed and populated. As ComCat came online in 2013, regional networks and the NEIC have over time stopped contributing event information to the ANSS catalog. As it continues to be the best resource for event information prior to 2013 the NCEDC and UCB continue to host the ANSS Composite Catalog providing event data including 2012 (<http://www.quake.geo.berkeley.edu/anss/catalog-search.html>), until the ANSS Combined Catalog (ComCat) is fully populated with historical information.

- 2.2 *Swarm: Webservices for Waveform Display:* BSL Applications Programmer Ivan Henson added the capability the program swarm (<http://www.avo.alaska.edu/Software/swarm/>) to use web-services to harvest data for display. In the past it was limited to fissures (which is now deprecated) and earthworm. These two services sometimes caused firewall problems.
- 2.3 *Linux migration:* The list of UCB activities supported as part of the implementation of AQMS, datacenter services and databases under linux include: migration of web services and the breq_fast system; migration of the USGS MP real time and post processing databases; migration of the DART systems at USGS MP and UCB; migration of the "simple wave servers" (SWS) for the archive and DART.
- 2.4 *New data sets:* The NCEDC now hosts a variety of new data sets, including both real data from a broadband deployment at the Geysers, and synthetic data, such as the "fake quakes" developed for testing geodetic and point source algorithms for earthquake early warning. In addition, previously missing data from NP stations were archived. These geophysical data sets are available at <http://ncedc.org/ncedc/other-geophysical-datasets.html>. The NCEDC also hosts a public data center for event parameters and waveforms from sites monitored under DOE's Geothermal Monitoring Program, funded by the Department of Energy through Lawrence Berkeley National Laboratory (LBNL). The largest portion of these data are from the Geysers area, but they include events and waveforms from other western states. This work is funded by DOE through LBNL. We have QC'd metadata from the geothermal networks and are importing waveforms and event data. Another data set currently collecting at the NCEDC is from a deployment of rotational seismometers at the Geysers. The sensors were deployed by the USGS MP field techs and have been collecting waveforms since Spring 2012. Metadata and data are available at the NCEDC.
- 2.5 *Archive "clean up":* During recent QC activities at the NCEDC, including the effort to add waveforms to existing event packages, a variety of waveform issues were discovered. Many of them have been resolved, including a bug in the K2 software which provided corrupt data.
- 3) *Earthquake Response and Reporting:* We continue to collaborate with our partners at USGS MP to ensure rapid and reliable reporting on earthquakes in Northern California, including determination and review of moment magnitudes and moment tensors. When USGS MP is not available due to government shutdown, we at UCB take over full response.
- 4) *EMAG (Enterprise Messaging Service):* Pager service in the Bay Area began degrading before the project began in 2015. UCB implemented the EMAG, or Enterprise Messaging Service, from Verizon, to send earthquake information and system monitoring alerts via text messages to the cellular phones of USGS MP and UCB staff. The service was finally implemented in the Summer of 2018 at UCB in the Autumn of 2018 at USGS MP. EMAG is now the service providing information on earthquakes and system monitoring in the NCSS.
- 5) *BK/BP Station Web Pages:* The BSL webpages were updated during the project interval, and the station web pages (<http://earthquakes.berkeley.edu/networks>) got a new look. The "quick look" waveform view page (<http://ncedc.org/bdsn/quicklook.html>) and the associated "Make Your Own Seismogram" web page (http://ncedc.org/bdsn/make_seismogram.html) were also updated. We are planning to add quicklook pages for NC stations as well.
- 6) *New BK/BP Stations:* Over the course of the past five years about 45 stations have been added to the BK/BP networks operated by UCB, with TremorScope funding from the Moore Foundation, and with support from the state and federal EEW efforts. In the first 2 years of the project, three TremorScope borehole/surface stations were completed, instrumented, and came online in the area south of Parkfield. Each station has a broadband/strong motion sensor package that is digitized downhole and a surface accelerometer. A new borehole site near the California Memorial Stadium (CMSB) was instrumented with a geophone, digitized at the surface, and a surface accelerometer; the original site had been destroyed during the Memorial Stadium remodel, and the Campus drilled a new borehole for our equipment. With federal EEW funding and GFE, eight stations from the original and Cascadia TA deployments were reinstrumented with broadband seismometer and accelerometers and are contributing data. Additional stations were scouted, permitted, constructed and instrumented with the state and federal funds and GFE over the past 2 years, bringing the total of new stations to 45. The EEW instrumentation installed included Q330S+ and Minimus data loggers; Reftek 151b, Guralp CMG-3T and MBB2 seismometers; and Fortis and Episensor accelerometers. All equipment was tested in the Byerly Vault before deployment. We have developed and deployed site infrastructure to maximize the capacity to remotely monitor and troubleshoot station equipment.

- 7) *BK/BP Station Improvements, Repairs and Problems.* In the second half of the five year project, field activities primarily concentrated on the construction and installation of new stations. Nonetheless, station improvements and repairs continue to be a priority. In the first year of the project, the primary goal was to complete telemetry upgrades necessitated by the pending loss of Frame Relay. Many stations are now sending data by cell modem, although some have transitioned to “host internet” – as at Columbia College. The transition to cell modems resolved telemetry problems at a number of stations that had been offline for several months, including, for example, KCC. For BDM, where the new cell modem worked briefly, we finally got telemetry back when the host, Black Diamond Mine Regional Park, got optical fiber internet service. No new telemetry solution has yet been implemented for GASB, where data continue to be collected onsite, and retrieved by “sneakernet”. During telemetry or other site visits accelerometers have either been upgraded from 2g to 4g or replaced with a 4g sensor (a process not quite completed even now). A recurring problem with Episensors is the sudden appearance of noisy channels, which can only be alleviated by the replacement during a site visit. At some sites other sensors also exhibit problems including: recurring need to recenter Reftek 151B seismometers; changing (aging) responses in STS-1 seismometers; recentering problems with CMG-3T seismometers; and STS-2 seismometers for which the feedback system dies. We have noticed problems with many of the Baler44s recording data in the network. They do not respond to pings. It is not completely clear whether they are still recording data or not. Another recurring field task has been the effort to improving data from the HRSN stations, both in terms of data return and data quality. The telemetry topology of the HRSN was recently modified, improving and simplifying the data, although data quality continues to suffer as the equipment in the field ages. Another effort at the HRSN and other borehole sites with Basalt data loggers was the replacement of failed CF cards, a fatal problem with the Basalts, since the operating system is also on the CF cards. We continue to work through problems at our “original stations”, those operated by UCB before the EEW buildout effort. For example, the station BRIB was down after it was flooded during heavy rain in December 2014. The broadband/strong motion system has been reinstalled at location very near by which is much less likely to flood. Brief reports for several other sites are included in the following table.

Table 2: Summary of Some Station Problems

HAST	2019	Recently refurbished; accelerometer installed; still occasional telemetry problems
HATC	2016	Optical fiber telemetry upgraded, Baler14 replaced with Baler44
HELL	2016-present	Flooded, and equipment replace. Flooded again. Plan to install new equipment, soon
HOPS	2019-present	STS-1 horizontal seismometer has problems
HUMO	2018	Owner through whose land we accessed/powerd the site requested that we shut it down. We hope to contact the new landowner soon and bring the site back online
MOD	2019-present	Seismic sensors and telemetry have problems. Need site visit to refurbish, replace VSAT with cell modem
WDC	2016, 2018	Flooded, then burned (Carr fire). We are planning to reinstall in the next year
YBH	2015-present	Slow degradation of one of the STS-1 horizontal components

- 8) *Metadata:* We regularly review metadata for all the stations for which we collect data in the NCEDC, and which we use in real time operations. This includes data from the BK, BP, BG, CE, PB, PG, WR, NC, NN and NP stations. We also regularly use tools we have developed for reviewing sensor operation and metadata. We also work with NCSN and NSMP personnel to prepare and QC metadata and dataless SEED volumes for NSMP stations. They are available at the NCEDC (<http://www.ncedc.org/ftp/pub/doc/NP.info/>).
- 9) *ShakeMap Operations:* We rapidly produce and publish ShakeMaps for Northern California earthquakes. We operate ShakeMap 3.5 and recently modified our standard parameters to use the Atkinson and Boore GMPE and the Worden 2012 GMICE in the NCSS. UCB is running a test system with ShakeMap 4.0 for the NCSS. We are working within the CISN ShakeMap Working Group to develop a web page framework to host ShakeMaps from version 4.0 on the CISN web pages. When we upgrade to ShakeMap 4.0, we will rerun and resubmit all ShakeMaps. UCB also contributes ground motion products from UCB stations to NEIC in real time using a procedure developed and implemented by Pete Lombard in collaboration with Bruce Worden. We have been collaborating with the ShakeMap working group, in particular with colleagues from CGS and USGS Menlo Park to define, revise and evaluate the time windows that should be used to harvest and associate ground motion parameters from earthquakes for use in ShakeMap. Using existing datasets, we have defined a new set of rules, based on magnitude, distance and observed amplitude decay

in the western US (WUS) and central and eastern US (CEUS). They are under discussion in various CISON working groups. The intention is that they will be implemented in upgraded versions of various AQMS software packages.

- 10) *"Historical" Northern California waveform and parametric data:* We have resumed efforts to improve event gathers for "historical" NC events - those prior to 2006/11/29. This has been integrated into the NCSS catalog improvement effort detailed above.

Table 3: Table of Seismic Stations

Summary Statistics for Regional/Urban Seismic Network	Number ^{\$}	Station Response Information in dataless SEED volume(s)
Total no. of stations operated and/or recorded	124/2,230	SEED responses for all SNCL's we record are available through 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 [#]
Total no. of channels recorded	5,319/21,604 ^{&}	
No. of short-period (SP) stations	37/1,061	
No. of broadband (BB) stations*	86/264	
No. of strong motion (SM) stations*	102/1145	
No. of stations maintained & operated by network	124	
No. of stations maintained & operated as part of ANSS	124 [%]	

^{\$} In each case, the first number is for stations or SNCLs with either BK or BP as network codes, stations of the networks the BSL operates. The second number includes all of the data collected at the USGS MP and forwarded for archival to the NCEDC, or collected from stations operated by other networks and collected at UCB. We archive data at the NCEDC from more than 15 other seismic networks, which are not listed here. Both numbers include state-of-health channels where available.

[&] These are the total number of unique channels (unique "station.network.channel.locationcodes", or SNCLs) recorded in the past year at the NCEDC.

^{*} We have added a station category "Strong Motion". Seven BK stations have surface accelerometers associated with borehole sensors (RFSB, TCAS, TSCS, TRAY, CMSB) or only surface accelerometers (SCCB, BL88). The additional SM stations listed as being archived at the NCEDC may also be listed as NC stations that have short period vertical sensors (entered in the SP row) in association with a strong motion sensor, or are NP stations within our region.

[%] Five of the stations from the BK network are ANSS backbone stations. In addition, we operate one GSN station (CMB) and one CTBTO auxiliary station (YBH). We contribute data from 10 stations in real time (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 Seismic System, the joint operation of the BSL and USGS MP as part of the California Integrated Seismic Network of the ANSS. Data from BK broadband/strong motion and strong motion only stations are contributing to the ShakeAlert EEW system. We also use data from neighboring networks, like NN, stations from the Cascadia Initiative, from the Plate Boundary Observatory (PB) and Southern California Seismic Network (CI) in our earthquake monitoring and information system.

[#] For 20 of the SNCLs for which we have waveforms in the archive, we currently do not have metadata. They are "historical" BK stations with digital data from before 1991. We continue to work to develop metadata for these BK SNCLs.

- 11) *Implementing Earthquake Early Warning:* The Production Prototype Earthquake Early Warning system has been online since February 2016, and extended to the entire West Coast in Summer 2017. The system became a public in California on October 17, 2019. At the BSL, we continue to monitor performance of the system and contribute improvements. We are making progress toward integrating GNSS into EEW processing -- Glarms is running West Coast wide, with data from Southern California, Northern California and the Pacific Northwest. Doug Neuhauser, under recall, improved the seedlink protocol and servers to allow (a) incompletely filled mseed packets to be transferred, and (b) shorter mseed packets to be transferred. He has now developed a version of orb2slink that will allow rapid, low latency transfer of mseed data to a seedlink server for transfer between data centers, particularly to allow low latency data to be transferred from University of Nevada Reno (NN) stations. This allows seedlink to be used to transfer low-latency mseed data for earthquake early warning processes, while optimizing (lowering) the required bandwidth for data transfer. Neuhauser discovered a problem with the seedlink service in the Rock series of data logger. That software was written by ISTI. He documented and reported the problem to Kinematics and ISTI and a software fix may soon be available.
- 12) *GridMT scanning operating on RT data:* With past funding from the USGS through the NC NEHRP program, UCB 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 regularly reports on events off-shore of Northern California and Southern Oregon. For a variety of reasons, including lack of support, this program stopped running in 2019.
- 13) *Real-time double difference (DD) event locations:* Double difference earthquake locations give a more focused view of faults and seismic sources. DD processing has been implemented within the AQMS system, and DD event locations are available through the NCEDC. Updates for the DD system to provide depth relative to the geoid are still ongoing.
- 14) *Participation in ANSS Working Groups* For years the CISN has had a "Standards Committee" to discuss and guide development and implementation in California of what is now the AQMS software. Peggy Hellweg of the BSL chairs that committee. With the implementation of AQMS at many of the Regional Networks, we have invited their proposals and participation for topics of interest. Stephane Zuzlewski chairs the Schema Change working group. In addition, Stephane Zuzlewski and Fabia Terra are members of the SIS working group. Peggy Hellweg and Fabia Terra participate in NIC conference calls and meetings, and Peggy Hellweg has participated in many ANSS working groups, including the ComCat, the Depth Datum and the Magnitude Implementation working groups. Several UCB staff members participate in the CISN's ShakeMap and Data Exchange working group, which coordinates the implementation of ShakeMap in California, provides input and standards for exchange of ground motion data, and is the California liaison with the ShakeMap team in Golden.

Data Management Practices

Describe briefly your state of progress toward meeting ANSS data management performance standards (standards 4.1, 4.2, 4.3, 5.1 and 5.2).

(4.1) Waveforms from some BK stations are shared with partner networks, including CI, NN, PN, ATWC, PTWC and NEIC. As soon as waveforms arrive at Berkeley, they are transferred to ring buffers that are available to the partner networks. They are available within 30 s of their arrival at the data center. We no longer ship waveforms directly from the station to the CI datacenter for processing, at their request. We continue to receive waveforms from 1 or 2 CI seismic stations at the datacenter in Berkeley, at our request. We can now "hit" CI wavepools to collect data for realtime processing. Data from CI wavepools are available for waveform gathers for NC events and waveforms from NC and BK stations are available for waveform gathers for CI events. (4.2 & 4.3) Amplitudes and picks are shared in the NCSS between the data centers at UCB and USGS MP. They are available through network services essentially as they are produced (<10 s). Amplitudes for strong motion purposes are harvested soon after an earthquake and are available to the Strong Motion Engineering Data Center (SMEDC), or to our CISN partners at the CI network, usually within 10-15 minutes of the event. We are working to share amps and picks with CI, and also with NN to exchange strong motion amplitudes particularly for events on both sides of the California/Nevada border. We will begin to work with neighboring AQMS networks to share picks and amplitudes with them through network services. (5.1) Waveforms arriving at the NCEDC are placed in the DART (Data Available in Real Time) within seconds of their arrival. There they are available to internal and external users. Quality controlled data are placed in the archive within three days of their production. (5.2) As soon as an event is "completed", that is, it has a hypocenter and possibly a magnitude, it is placed in the database, and becomes available for catalog searches (<10 minutes). Hypocenters for events with more than 25 picks are sent by PDL within 30 s of their occurrence, and event information is updated by PDL with improved origin information, magnitudes and review status as soon as new information becomes available.

Progress on ANSS Integration

Describe briefly details on coordinated exchange of real-time waveform data, real-time picks, amplitudes/durations, and earthquake locations to other ANSS networks .

Waveform exchange: The dual data feed directly from stations between Northern and Southern California has ceased due to lack of funding and changes in telemetry, except that at our insistence, UCB continues to receive data directly from GSC, which has internet based telemetry. No data go directly to Southern California from UCB at their request. We now receive data from the Southern California wavepools for: ARV, BAR, BEL, DPP, FMP, HEC, PLM, RVR and TIN, as well as for a suite of other stations within 100 km of the Byerly-Gutenberg line. The harvesting of data from Southern California wavepools has been coordinated with USGS MP, so that if one of our data centers goes down, the other will still have a good view of Southern California seismicity. Southern California waveforms are picked, amps are produced, they are collected in event waveform gathers and they are used in moment tensors, fault plane solutions and finite fault models. Southern California receives data from

UCB wavepools for whatever stations they want. We also receive data from UCSD orbs (KNW, LVA2, PFO, RDM and SOL). We currently provide realtime waveforms to NEIC (CMB, HOPS, SAO, WDC, HUMO, JCC, MOD, MCCM, ORV and YBH). We receive, use and archive waveforms from UNR broadband stations (BEK, OMMB, PAH, PNT, RUB SRV3, SRVL, TVH and WAK). This set of stations is changing as UNR deploys additional EEW stations. We now also receive data in real time from several CGS stations that are contributing to EEW. The data from these stations are also being used in real time processing. UCB and USGS MP are developing a plan of waveform exchange with PNSN. We also share our waveform data with NN, PNSN, PTWC and ATWC in realtime.

Event parametric data: We currently send event information, including picks, amplitudes, durations and magnitudes to NEIC shortly after an earthquake has been located. We have been operating a test system for the exchange of picks and amplitudes with Southern California for several years. We have not yet progressed to the stage of operating such exchange in production. We are a primary partner working with the Earthquake Hazards group in Golden to implement PDL for the robust and rapid exchange of earthquake information, including the development of converters from AQMS to QuakeML for many standard earthquake information products, including fault plane solutions and moment tensors, and the definition of add-on products such as fault plane solution or moment tensor images.

ShakeMap: We produce and publish ShakeMap to the CISEN web pages (<http://www.cisn.org>) as well as to the Earthquake Hazards group in Golden for publication on the USGS web pages. We have worked with our Southern California partners and the California Geological Survey (CGS) to provide a redundant "datafull" ShakeMap service. Now CGS also provides ShakeMap backup for California, producing ShakeMap with data from its stations, should the primary (NC or SC) ShakeMap be delayed.

Production coordination and redundancy: We operate mirrored redundant earthquake reporting systems of AQMS software at UCB and USGS MP. To ensure robust performance, we exchange picks, amplitudes, codas and ground motion parameters in realtime. All information flows continually into both reporting systems. UCB currently operates two web servers for moment tensor review, since the USGS MP has not been able to provide appropriate openings in DoI firewalls. We coordinate ShakeMaps throughout California (see above). We also discuss and coordinate ShakeMap production with NEIC, UNR and PNSN through CISEN ShakeMap Working Group conference calls. In case of events near our reporting boundaries or off the coast of Oregon, we coordinate with the appropriate partner.

Parameter Exchange: The NCSS has been sending ground motion parameters (PGA, PGV, PGD, SAx) via PDL for several years using procedures and code developed by Pete Lombard and Bruce Warden.

Network Highlights

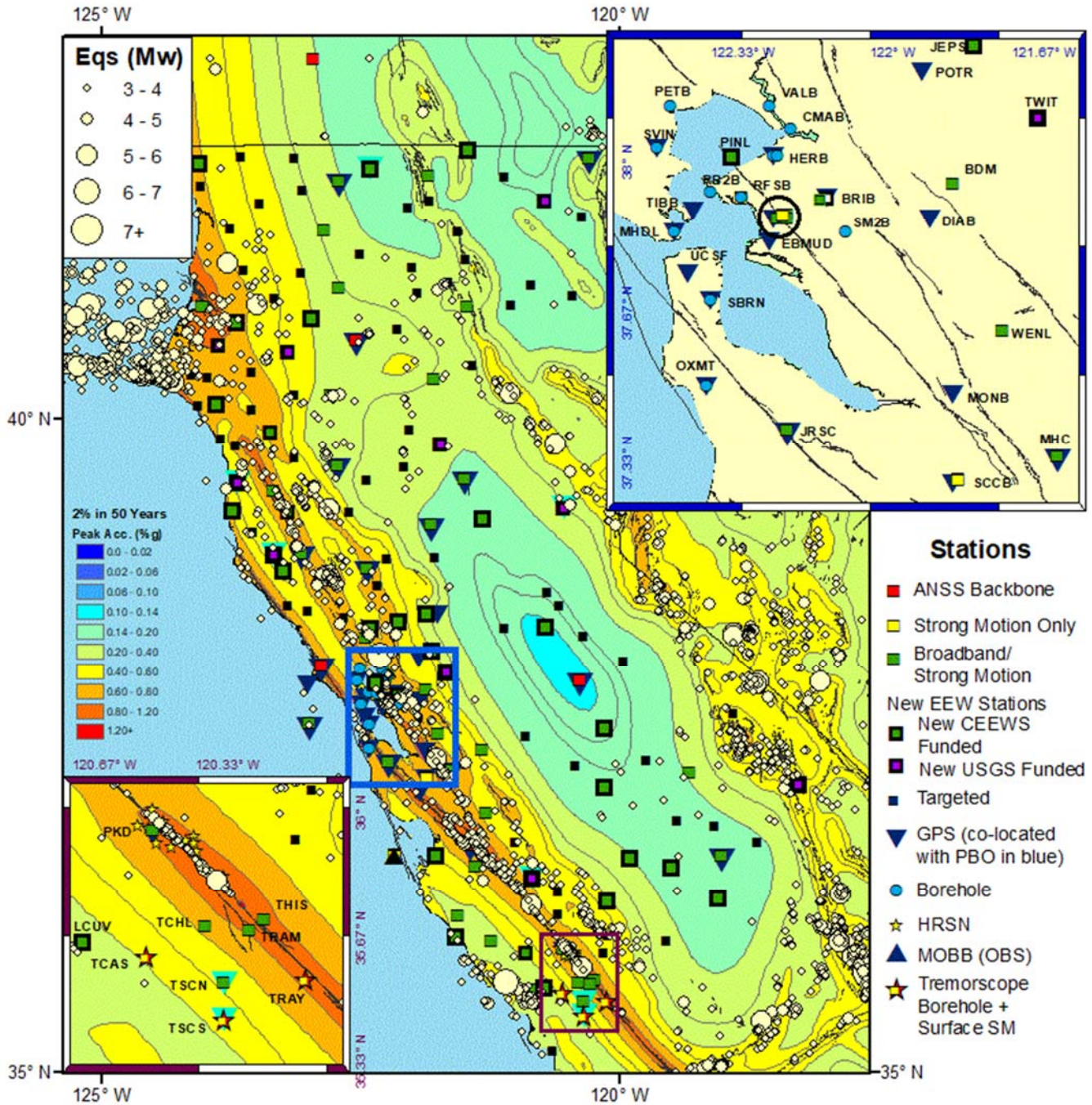


Figure 1: Map illustrating the distribution of geophysical stations operated by the BSL in Northern and Central California (network codes BK, BP, also BARD geodetic stations). Green and red squares show sites with broadband/strong motion equipment, with red squares indicating ANSS stations. Yellow squares indicate stations with strong motion sensors at the surface. The black square denotes MOBB, our ocean bottom seismometer (which currently remains offline due to power and cable problems). Open squares show the locations of stations to be adopted and instrumented to improve network coverage for EEW; during this project, more than 40 sites been brought online, and five more have been constructed but are not yet online, mainly due to lack of telemetry. All stations contribute to earthquake monitoring in the NCSS and the broadband and strong motion sites contribute to EEW. We have funds from the state to construct 60 more stations. Black squares indicate planned EEW sites, some of which have already been permitted and are scheduled for installation. Inverted triangles are sites from the BARD network with geodetic antennas and receivers; 16 are currently colocated with broadband/strong motion equipment. Bay Area borehole sites are indicated by light blue circles (downhole geophones and some with downhole accelerometers), gold stars (High Resolution Seismic Network stations in the Parkfield area, with downhole geophones), and blue stars (Tremorscope boreholes with downhole digitizers, broadband seismometers and accelerometers). The inset map to the upper right shows the stations in the Bay Area, with the densely sited stations in the circle being SRB1 (geodetic), BRK, BL88, VAK, BL67 and BKS (from left to right). The inset on the lower left shows detailed locations of the stations installed in and around Parkfield, CA. The seismicity (circles) indicate earthquakes in the reporting region since 2000 with magnitudes greater than 3.0.