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HIGH-RESOLUTION MONITORING OF THE HAYWARD FAULT

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Non-Technical Project Summary

This project addresses the seismic potential hazard presented by large earthquakes on the Hayward Fault by collecting high-resolution seismic data. It provides continuous 3-component waveform data coverage of seismic signals down to very low amplitude from microearthquakes and possible nonvolcanic tremors in the Bay Area. It provides basic information needed to study earthquake source properties, the detailed structure of the northern Hayward Fault, the spatio-temporal distribution of deep fault deformation, and fault roughness and strength properties. It also contributes to real-time seismic monitoring efforts by providing information for event phase determinations at numerous Bay Area locations.

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ABSTRACT

The primary role of the borehole network project along the Hayward failt is to complement surface networks by adding 3-component waveform coverage of very low amplitude seismic signals typically associated with very low magnitude seismicity and nonvolcanic tremor. These data are primarily used for fundamental research on fault zone and earthquake processes and to provide information for phase determinations for real-time seismic monitoring. The high sensitivity to low amplitude is being used to monitor for nonvolcanic tremors in the Bay Area. Over time, data from this project has spawned a variety of research into the distribution of strain accumulation along the Hayward Fault, micro-foreshock and after-shock activity, high-resolution fault structure, earthquake recurrence and scaling, and mapping of deep fault creep from microearthquake recurrence. Borehole network data ***contributes to the National Earthquake Hazards Reduction Program (NEHRP)*** by facilitating research supported by NEHRP and complementary research by investigators from other nations, and by providing fundamental input for models of spatial-temporal clustering of earthquakes, triggering of events, and on the systematic variations of deep slip rate in active fault zones. Additionally, the real-time monitoring of fault-zone process provides one of the rare hopes for understanding and tracking the nucleation of potential damaging earthquakes, an outcome, if eventually realized, that would aid significantly in reducing losses from earthquakes.

NON-TECHNICAL ABSTRACT

This project addresses the seismic potential hazard presented by large earthquakes along the Hayward and Rodgers Creek faults with high-resolution borehole recordings of low amplitude seismic signals in a region where several moderate to large earthquakes have occurred. It provides general information on earthquake source properties, on the detailed structure of the northern Hayward Fault and Rodgers Creek step-over, on the spatio-temporal distribution of deep fault slip, and on fault roughness and strength. The unique data and consequential findings have significant implications for earthquake source dynamics, for earthquake forecasting, and for scaling relations among earthquake source parameters. Sequences of near-identically repeating small earthquakes in the area are also providing a new method for monitoring the changing deformational strain field at seismogenic depth. Data and research results from this network also provide fundamental input to models of earthquake forecasting, on spatial-temporal clustering of earthquakes, on triggering of events, and on the systematic variations of slip rate on an active fault. This information is critical to earthquake risk estimation. The real-time monitoring of these fault-zone processes provides one of the rare hopes for understanding and tracking the nucleation of potential damaging earthquakes, an outcome, if eventually realized, that would be do much in reducing losses from earthquakes. Over time, the major investment operating and maintaining the data collection for the borehole network has produced a unique baseline of fault-zone behavior with distinct features observed rather than theorized, a body of observations that must be incorporated in new models for fault-zone deformation. We have continued to execute a basic program of operation, maintenance and archival of the network and network data and have continued our research program using the data in the study of the spatio-temporal details of microearthquake dynamics, wave propagation slip-rate variations and nonvolcanic tremor activity.

FINAL TECHNICAL REPORT:

HIGH-RESOLUTION MONITORING OF THE HAYWARD FAULT

Introduction

Complementary to the regional broadband network coverage in the Bay Area of California, a deployment of borehole-installed, wide-dynamic range seismographic stations is being established along the Hayward Fault and throughout the San Francisco Bay toll bridges network (Figure 1). This network is a cooperative development of the BSL (Berkeley Seismological Laboratory) and the USGS, with support from USGS, Caltrans (California Department of Transportation), EPRI, the University of California Campus/Laboratory Collaboration (CLC) program, LLNL (Lawrence Livermore National Laboratory), and LBNL (Lawrence Berkeley National Laboratory). Efforts at ongoing development of the network have also recently been enhanced through coordinated efforts with the Mini-PBO project which is partially funded by NSF and by the member institutions of the PBO project.

The purpose of the network is threefold: 1) to lower substantially the threshold of microearthquake detection, 2) to increase the recorded bandwidth for events along the Hayward fault, and 3) to obtain bedrock ground motion signals at the bridges from small earthquakes for investigating bridge responses to stronger ground motions. A lower detection threshold increases the resolution of the fault-zone seismic structure; allows seismologists to monitor the spatial and temporal evolution of seismicity at magnitudes down to M ~> -1.0, where earthquake rates are many times higher than those captured by surface sites; allows researchers to look for pathologies in seismicity patterns that may be indicative of the nucleation of large damaging earthquakes; and allows scientists to investigate fault and earthquake scaling, physics and processes in the San Francisco Bay Area. This new data collection will also contribute to improved working models for the Hayward fault. The bedrock ground motion recordings are also being used to provide input for estimating the likely responses of the bridges to large, potentially damaging earthquakes. Combined with the improved Hayward fault models, source-specific response calculations can be made as well.

The Hayward Fault Network (HFN) consists of two parts. Part 1, the Northern Hayward Fault Network (NHFN), is operated by the BSL and currently consists of 28 stations with various operational status, including those located on Bay Area bridges and at borehole sites of the Mini-PBO (MPBO) project. This network is considered part of the BDSN and uses the network code BK. Part 2, the Southern Hayward Fault Network (SHFN), is operated by the USGS and currently consists of 5 stations. This network is considered part of the NCSN and uses the network code NC. This project and report is focused on the NHFN and activities associated with the BSL operations.

Reducing losses from Earthquakes in the U.S. A better understanding of earthquake physics, earthquake recurrence models, and fault zone processes are critical to reducing losses from earthquakes in the U.S., and this project is arguably fundamental to those goals. Results obtained from this data collection and research effort provide unique information on the strain accumulation on faults at depth, estimation of the strength and strength heterogeneity of earthquake generating faults (i.e. fault roughness), and on scaling properties of earthquake recurrence times and rupture parameters, all of which are critical input for accurate earthquake forecasts, fault rupture models, and ground motion and earthquake hazard estimation. Uniquely, through the study of characteristically repeating small earthquakes this work also promises to provide direct tests of earthquake forecast models by making predictions based on these models and assessing their success rates on time scales of months to a few years as opposed to decades to centuries as required for similar tests using large magnitude events.

NHFN Overview

The five MPBO sites in the NHFN have 3-component borehole geophone packages. All the remaining HFN sites have six-component borehole sensor packages. The packages were designed and fabricated at LBNL's Geophysical Measurement Facility by Don Lippert and Ray Solbau, with the exception of site SFAB. For the non-MPBO sites, three channels of acceleration are provided by Wilcoxon 731A piezoelectric accelerometers, and three channels of velocity are provided by Oyo HS-1 4.5 Hz geophones. Velocity measurements for the MPBO sites are provided by Mark Products L-22 2 Hz geophones. The 0.1-400 Hz Wilcoxon accelerometers have lower self-noise than the geophones above about 25-30 Hz, and remain on scale and linear to 0.5 g. In tests performed in the Byerly vault at UC Berkeley, the Wilcoxon is considerably quieter than the FBA-23 at all periods, and is almost as quiet as the STS-2 between 1 and 50 Hz.

Sensors are generally installed at depths of about 100 m, but several sites have sensors emplaced at depths of over 200 m, and the Dumbarton bridge sites have sensors at multiple depths. During initial stages of the project, the NHFN sensors provided signals to on-site Quanterra Q730 and RefTek 72A-07 data loggers.

Fourteen of the NHFN sites have Quanterra data loggers with continuous telemetry to the BSL. Similar to BDSN sites, these stations are capable of on-site recording and local storage of all data for more than one day and have batteries to provide backup power. Signals from these stations are digitized at a variety of data rates up to 500 Hz at 24-bit resolution.

The NHFN data loggers employ casual FIR filters at high data rates and acausal FIR filters at lower data rates. Because of limitations in telemetry bandwidth and disk storage, 9 of these sites transmit one channel of 500 sps continuous data and 90 sec., 500 sps triggered data snippets for the remaining channels. The Murdock, Hutt, and Halbert (MHH) event detection algorithm (Murdock and Hutt, 1983) is operated independently at each station on 500 sps data for trigger determinations. Continuous data for all channels at reduced rates (20 and 1 sps) are also transmitted to and archived at the BSL. The 5 MPBO sites transmit continuous 100, 20 and 1 sps 3 component data streams that are also archived at BSL.

The remaining 14 sites of the NHFN have in the past recorded data using RefTek data loggers. These sites do not have continuous telemetry for acquisition and in the past required visits from BSL staff for data recovery. Collection of data from these sites has been discontinued, but efforts are underway to upgrade them with Quanterra Q4120, Q730 or Q330 data loggers and continuous telemetry. Data from the NHFN are archived at the NCEDC (Northern California Earthquake Data Center).

Station Maintenance

Ongoing network maintenance involves regular inspection of the collected seismic waveform data and spectra for nearby seismic events, and also from noise samples. Other common problems include changes to background noise levels due to ground loops, failing preamps, as well as power and telemetry issues. Troubleshooting and remediation of problems often require a coordinated effort with a technician at the BSL to examine seismic waveforms and spectra as the field technicians are still on site. BSL technicians regularly review data and assist in troubleshooting.

NHFN Station Maintenance Synopsis: The NHFN station hardware has proven to be relatively reliable. Nonetheless, numerous maintenance and performance enhancement measures are still required. Below is a synopsis of maintenance efforts performed recently for several NHFN stations that serves to illustrate some of the ongoing maintenance and enhancement measures that are typically performed.

BBEB: Ran radio tests on Wilan link to Space Sciences Lab at 18 dBm and at maximum power (23 dBm) to ascertain effect on dropped packets. At 24 dBm power, the throughput was 6 times higher than at 18 dBm power and the number of dropped packets reduced from 4.6% to 0.03%.

BRIB: Numerous frame relay telemetry problems were encountered during August and September, and the station was visited several times to troubleshoot and correct the problem.

CMSB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up.

CRQB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up and was functioning normally.

HERB: Velocity channel was found in September to not be responsive to events. The problem was traced to a blown fuse in the power system, although it is unclear as to how that problem effected the responsiveness of the velocity channel.

RFSB: Visited station several times to repair frame relay and power supply problems.

SMCB: Quanterra hung after 8/17 reboot. The power was manually recycled, and the Quanterra came back up.

W02B: Telemetry link went down in October and again in December due to an antenna problem.

Quality Control: A commonly used check on the calibration of the borehole installed network, is to compare the bandpass filtered (0.3-2 Hz) ground velocity data recorded at NHFN and MPBO stations for large teleseismic earthquakes. As an example, a M 7.5 intermediate focus teleseism that occurred in Peru at a depth of 115 km is shown in Figure 2.

Another practice for quality control is the assessment of power spectral density (PSD) distributions for the network stations. Shown in Figure 3 are power spectral density distributions of background noise for a sample of 13 NHFN land and bridge site stations. In general, background noise levels of the borehole HFN stations are more variable and generally higher than those of the Parkfield HRSN (High Resolution Seismic Network) borehole stations (the design goal for the NHFN was to attempt to match the performance of the HRSN). This is due in large part to the significantly greater level of cultural noise in the Bay Area, and to the fact that noise reduction efforts on the much more recently installed NHFN stations are still underway. For example the two noisiest stations (i.e. BBEB and W02B) are located on the Bay Bridge, which is currently undergoing earthquake retrofit and east span reconstruction. These stations have also only recently come back on-line with upgraded infrastructure and instrumentation, so the full complement of noise reduction modifications have not yet been implemented.

On average the MPBO component of the NHFN sites is more consistent and somewhat quieter. This is due in large part to the greater depth of the MPBO sensors, the locations of MPBO stations in regions of generally less industrial and other cultural noise sources, and possibly to the absence of powered sensors (i.e. accelerometers) in their borehole sensor packages.

One of the most pervasive problems at NHFN stations equipped with the Q4120 data loggers is power line noise (60 Hz and its harmonics at 120, 180, and 240 Hz). This noise reduces the sensitivity of the MHH detectors. Whenever a NHFN station is visited, the engineer at the site and a seismologist at the BSL work together to expedite the testing process, especially when attempting to identify and correct ground-loop faults which generally induce significant 60, 120, 180, and 240 Hz seismic signal contamination due to stray power line signal pickup, generally inductively coupled and aggravated by the presence of ground loops.

HHH

Geophone Calibration Test Equipment: Comparisons of the inferred ground accelerations generated by local earthquakes from co-sited NHFN geophone and accelerometer pairs show that the waveforms generally are quite coherent in frequency and phase response, but that their inferred ground accelerations differ significantly. At times, the amplitudes differ by up to a factor of ~2 while the times of the peak amplitudes are identical. This implies that the free period and damping of the geophones are well characterized. However, it also indicates that the generator constant is not accurate (assuming that the corresponding ground accelerations inferred from the accelerometers are accurate).

Generally speaking, the accelerometers, being an active device, are more accurate and also more stable than the geophones, so it is reasonable to assume that the most likely reason for the difference is that the assumed generator constants for the geophones are inaccurate. Rodgers et al. (1995) describe a way to absolutely calibrate the geophones in situ and to determine their generator constant, free period and fraction of critical damping. The only external parameter that is required is the value of the geophones inertial mass.

We have built a calibration test box which allows us to routinely perform the testing described by Rodgers et al. whenever site visits are made. The box drives the signal coil with a known current step and rapidly switches the signal coil between the current source and the data logger input. From this information, expected and actual sensor response characteristics can be compared and corrections applied. Also, changes in the sensor response over time can be evaluated so that adjustments can be made, and pathologies arising in the sensors due to age can be identified. Once a geophone is absolutely calibrated, we can also check the response of the corresponding accelerometer.

We are still performing the initial calibration tests and response adjustments for all NHFN stations as sites are visited for routine maintenance. We also plan to schedule routine re-tests of all sites to monitor for sensor responses changes through time.

Recent Activities

In addition to routine maintenance, operations and data archival, activities of the NHFN project during the funding period have also included numerous efforts at network expansion, quality control and data analysis.

New Installations: As originally conceived, the Hayward Fault Network was to consist of 24 to 30 stations, 12-15 each north and south of San Leandro, managed respectively by UCB and USGS. Due to funding limitations, however, progress has been slow and the original plan has been significantly modified. Fortunately and with additional Caltrans support continued development of the NHFN component of the project has been possible and is ongoing. This important contribution to the Hayward Fault Network has more than doubled the number of sites with instrumentation that would otherwise not have existed. Caltrans continues to provide holes of opportunity, so we have plans for additional stations that will bring the network geometry to a more effective state for imaging and real-time monitoring of the Hayward fault. Below are short summaries of activities over the past year related to the preparation, installation and activation of new NHFN stations.

San Francisco Bay and Richmond-San Rafael Bridges. The infrastructure at seven stations along the San Francisco-Oakland Bay Bridge (SFAB, W02B, W05B, YBAB, E07B, E17B, and BBEB) was upgraded with the installation of weatherproof boxes, power, and telemetry in anticipation of installing Q4120 data loggers and telemetering the data back to Berkeley. By June of 2003 both BBEB and W02B were brought on-line.

Land Sites. Agreements with Caltrans and St. Mary's college have been made to replace the post hole installation at St. Mary's college (SMCB) with a deep borehole installation. The hole is to be drilled by Caltrans as a hole of opportunity when the schedule of a Caltrans drilling crew has an opening. The site has been reviewed by UCB, Caltrans and St. Mary's college personnel, and we are now in the drilling queue. Depending on the geology at borehole depth, this site my either become a MPBO site (w/o accelerometers) or a standard land site installation including both geophones and accelerometers.

Caltrans has also provided funding for instrumentation of several other land sites which we will install as future Caltrans drill time becomes available. Currently we are considering sites for these additional holes-of-opportunity at Pt. Pinole, on Wildcat Mtn. in the north Bay. We are in the process of obtaining permission from the East Bay Regional Park District (EBRPD) to site a HFN station at the Point Isabel Regional Shoreline.

Mini-PBO. The stations of the Mini-PBO project are equipped with 3-component borehole seismometers and tensor strainmeters. As these stations have become operational, they augment well the HFN's coverage of the Bay Area (Figure 1). In the last year, SVIN and SBRN have added coverage to the north bay and west side of the south bay, respectively.

Quality control and Data Analysis: In order to monitor and capture the source spectrum of moderate down to micro-scale earthquakes, it is essential that the NHFN instruments operate at high precision and in an extremely low noise environment. Therefore, the stations record at high sample rate and their sensors are emplaced in deep boreholes to reduce noise contamination originating in the near surface weathered zone and from cultural noise sources. In addition, the reduction of noise at these stations through vigilant monitoring of actual seismic events plays a central part of our quality control effort.

Monitoring network health with moderate earthquakes. In Figure 4, we show a profile of the NHFN stations for a recent Ml 4.6 earthquake located about 60 km NW of Berkeley. Figures such as this are helpful for evaluating network health, and analysis of the waveforms and spectra assist in troubleshooting problems. As Figure 4 shows the network is performing very well, but there are some stations exhibiting problems. For example, the Bay Bridge site W02B shows high frequency noise, and OLNH and OXMT show sensitivity and dropout problems.

Microseismicity. As mentioned, a key aspect of quality control of the NHFN data is the analysis of actual seismic events. Seismic events of larger magnitude are relatively rare and generally provide more energy at lower frequencies. Hence in order to provide more frequent real events and quality control in the higher frequency band of the NHFN stations, analysis of recordings from the much more frequent microearthquakes are needed. Because real event analyses are relatively labor intensive and because of inadequate insufficient funding, traditional methods of event analysis have proven financially infeasible. To help circumvent these problems, efforts to develop new and improved analysis techniques are ongoing. We have developed and are currently testing some promising techniques that are particularly well suited to the analysis of similar and repeating microearthquakes. The advantages of similar and repeating event analyses for both quality control and scientific purposes are numerous, and the nature of the seismograms from these types of events make automated, rapid and robust analysis possible.

Towards this end, we are currently testing three new algorithms which we have developed: 1) a phase onset time detector with sub-sample timing resolution for improved absolute pick time accuracy, 2) a pattern scanning recognition scheme to detect, pick, locate and determine magnitudes for small and very small similar events recorded either continuously or from among large volumes of noisy triggered data snippets, and 3) a phase coherency method for identification of characteristically repeating events sequences from among groups of similar event multiplets.

PHASE ONSET TIME DETECTION: The phase onset time detector makes use of the concept that the complex spectral phase data over the bandwidth of interest (i.e., where the SNR is sufficiently high) will sum to a minimum at the onset of an impulsive P-wave. The algorithm searches for the minimum phase time via phase shifting in the complex frequency domain over the bandwidth where the SNR is above 30 dB to identify the onset time of the seismic phase. The algorithm requires that the recorded waveforms be deconvolved to absolute ground displacement. This implicitly requires that any acausality in the anti-aliasing filtration chain, such as the FIR filters used in the BDSN Quanterra data loggers, be removed. The algorithm typically resolves P-wave onset times to one-fiftieth of the sample interval or better.

PATTERN SCANNING RECOGNITION: The Murdock-Hutt detection algorithms used by MultiSHEAR, which basically flags an event whenever the short-term average exceeds a longer-term average by some threshold ratio, is neither appropriate for nor capable of detecting the smallest seismic events where signal to noise levels approach those of spurious cultural and earth noise signals. This is because the increased sensitivity parameters needed for small event detection also result in a large fraction of false event triggers. The use of multiple station association filters to reduce the false trigger rates are also of limited value since many of the smaller events are only recorded with enough signal to noise to trigger at a few stations and noise triggers at high sensitivity also often appear to associate temporally at several stations. Added to this is this the exponential increase in the frequency of events with decreasing magnitude, which quickly makes analyst time requirements for comprehensive review and processing of the smallest events financially infeasible.

The approach we have been working on this year to help overcome these problems has been to enhance the effective signal to noise and to focus on identification and processing of some of the more scientifically significant events through the use of a cross-correlation based scanning approach, which scans known waveform patterns through either continuous or collections triggered event snippets (regardless of the triggered event noise levels). With this approach continuous or triggered waveform data that does not match selected patterns are ignored while waveforms that approximately match selected reference event patterns are flagged as newly identified earthquakes.

This approach is less comprehensive in that it only detects events that are somewhat similar in waveform character to the reference patterns. However, it can be generalized significantly by increasing the number of event patterns scanned or by using fairly low maximum cross-correlation thresholds for event flagging. Preliminary tests of our scanning code show that scans of 100 distinct event patterns can be scanned through a days worth of waveform data in ~ 75 minutes on one 900Mhz SPARC cpu when continuous seismic data is used. Scanning through collections of all triggered snippets is substantially faster, in proportion to the inverse fraction of total time spanned by the snippet data.

The approach also provides automated cross-correlation pick alignments that can be used for high precision relative locations and for automated low-frequency spectral ratio determinations for magnitude estimates. Clearly the method has potential for automatically cataloging a large fraction of the more numerous microearthquakes, and in conjunction with the special attributes of similar event groups, updates of the catalogs in an automated monitoring mode can provide near-real-time microearthquake information that can be a powerful tool for monitoring network performance of real event data. Future plans include development and implementation of an automated similar event scanning and cataloging scheme that will provide real-event data from similar small magnitude events for assessment of network health on a much more frequent basis (every few days).

Perhaps more significantly, the approach can also capture and rapidly catalog some of the most scientifically relevant events (e.g. repeats of characteristically repeating microearthquakes used for deep slip rate monitoring and swarms of similar events typically associated with foreshocks and aftershocks). The approach is also surprisingly good at detecting events over a wide magnitude range. Hence there is clear potential for using patterns from larger aftershocks (e.g. flagged by REDI) to rapidly and automatically develop a high-resolution picture of foreshock and aftershock activity associated with large mainshocks. Tests so far using waveform patterns from a 2.2Ml event have been able to detected and fully process similar events as low as Ml - 1.2 (a range of 3.4 magnitude units). Testing in this regard is continuing, but clearly the 3.4 magnitude range is a lower bound on the potential magnitude range attainable.

PHASE COHERENCY: A spectral phase coherency algorithm was developed to facilitate high resolution quantification of the similarities and differences between highly similar Hayward fault events that occur months to years apart. The resolution of the complex spectral phase coherency methodology is an order of magnitude better than the cross correlation method, which is commonly used to identify highly similar events with resolution of order of a few 10's of meters. This method, originally developed using NHFN borehole data, is now also being tested and refined using data from another borehole network (the HRSN). The goal of the testing and refinement is ultimately to develop a scheme for rapid and objective discrimination and identification of characteristically repeating microearthquakes sequences down to the lowest magnitude possible (where recurrence times are short and hence temporal resolutions are higher) at both Parkfield, and in the Bay Area of California.

Acknowledgments

Thomas V. McEvilly, who passed away in February 2002, was instrumental in developing the Hayward Fault Network, and without his dedication and hard work the creation and continued operation of the NHFN would not have been possible. Under Bob Nadeau's, Bob Uhrhammer's and Doug Dreger's general supervision, Rich Clymer, Doug Neuhauser, Bill Karavas, John Friday, and Rick Lellinger all contribute to the operation of the NHFN. Partial support for the NHFN is provided by the USGS through the NEHRP external grant program (grant no. 03HQGR0096). Expansion of the NHFN has been made possible through generous funding from Caltrans (grant no. 59A0245), with the assistance of Pat Hipley. Larry Hutchings and William Foxall of LLNL have also been important collaborators on the project in years past.

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

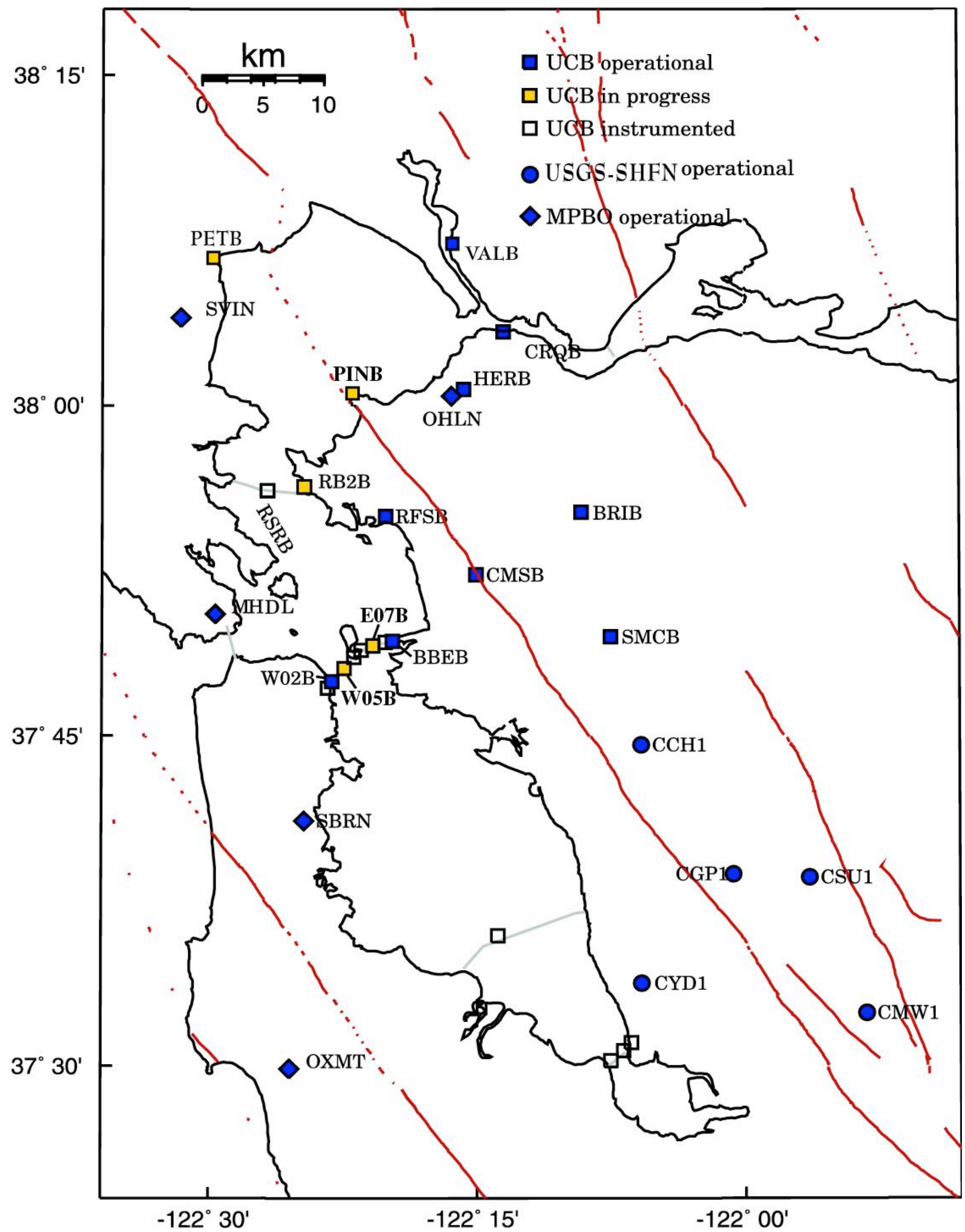

Figure 1. Map showing the locations of the HFN stations operated by the BSL (NHFN - squares) and the USGS (SHFN - circles) and Mini-PBO stations (diamonds) in the San Francisco Bay Area. Operational sites are filled blue/black, while sites in progress are yellow/grey. Other instrumented boreholes are indicated as open symbols.

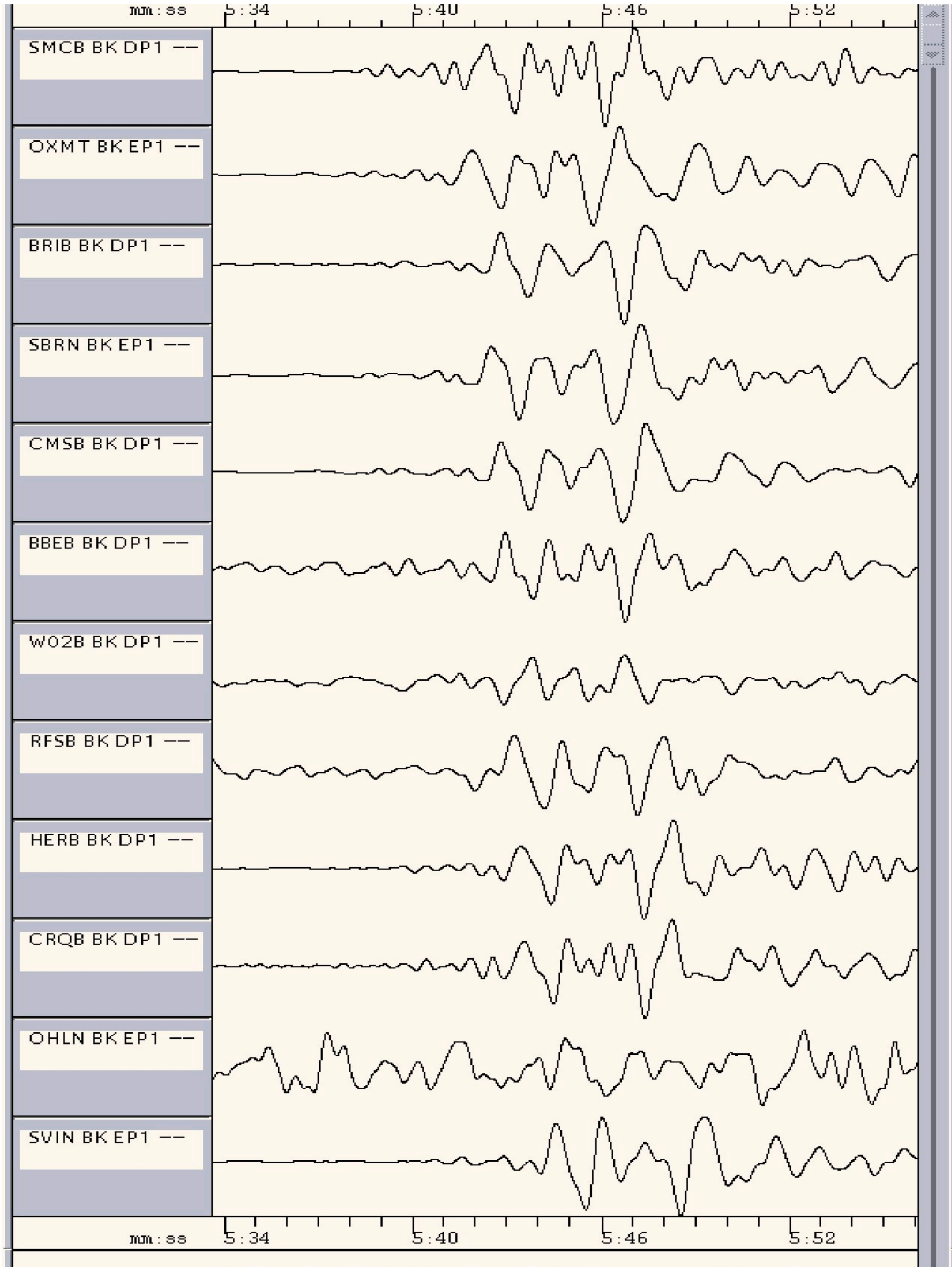

Figure 2. Plot of P-wave seismograms, recorded by 12 NHFN/MPBO borehole stations operating at the time of a major (Mw 7.5) intermediate focus earthquake occurring at 115 km depth and 60.8 deg. S55E of Berkeley, CA. Here vertical component geophone data have been deconvolved to ground acceleration, 0.3-2 Hz 6-pole, BP filtered and ordered by increasing distance (top to bottom). Of the 12 HFN, BB and MPBO vertical geophones that recorded the event, all the P waveforms are highly similar except for OHLN, which is noisy and not responding nominally to ground motion, and W02B, which has a low amplitude and distorted signal.

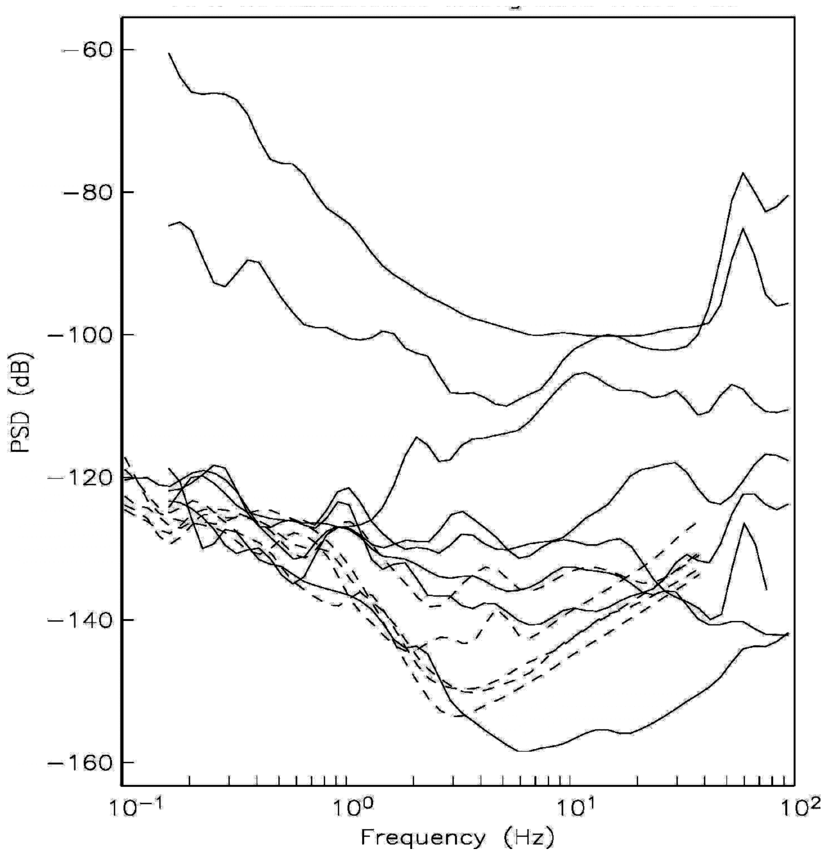

Figure 3 Plot showing typically observed background noise PSD for the NHFN borehole stations (including the MPBO in dashed lines) as a function of frequency. The data are from 2 am Local time on a Sunday morning. Note that there is considerable variation in the general level and structure of the individual station background noise PSD estimates. Of all the HFN stations, BRIB, the quietest borehole emplanted station, is also the farthest from local cultural noise sources. The signals from three of the stations (BBEB, SMCB and W02B) have 60 Hz noise, which is due to the presence of ground loops. The four noisiest stations (BBEB, CRQB, VALB and W02B) are near bridge anchorages. The PSD ranking of the stations of the stations at 4.6 Hz (near minimum PSD for most of the stations) is:

BRIB.BK.DP1 -156.46204
CMSB.BK.DP1 -151.96701
OXMT.BK.EP1 -151.28152
MHDL.BK.EP1 -149.33257
SVIN.BK.EP1 -148.51234
SBRN.BK.EP1 -138.45128
RFSB.BK.DP1 -137.71815
OHLN.BK.EP1 -132.80258
SMCB.BK.DP1 -131.35008
VALB.BK.EP1 -128.44617
CRQB.BK.DP1 -114.13147
BBEB.BK.DP1 -109.71306
W02B.BK.DP1 -98.61494

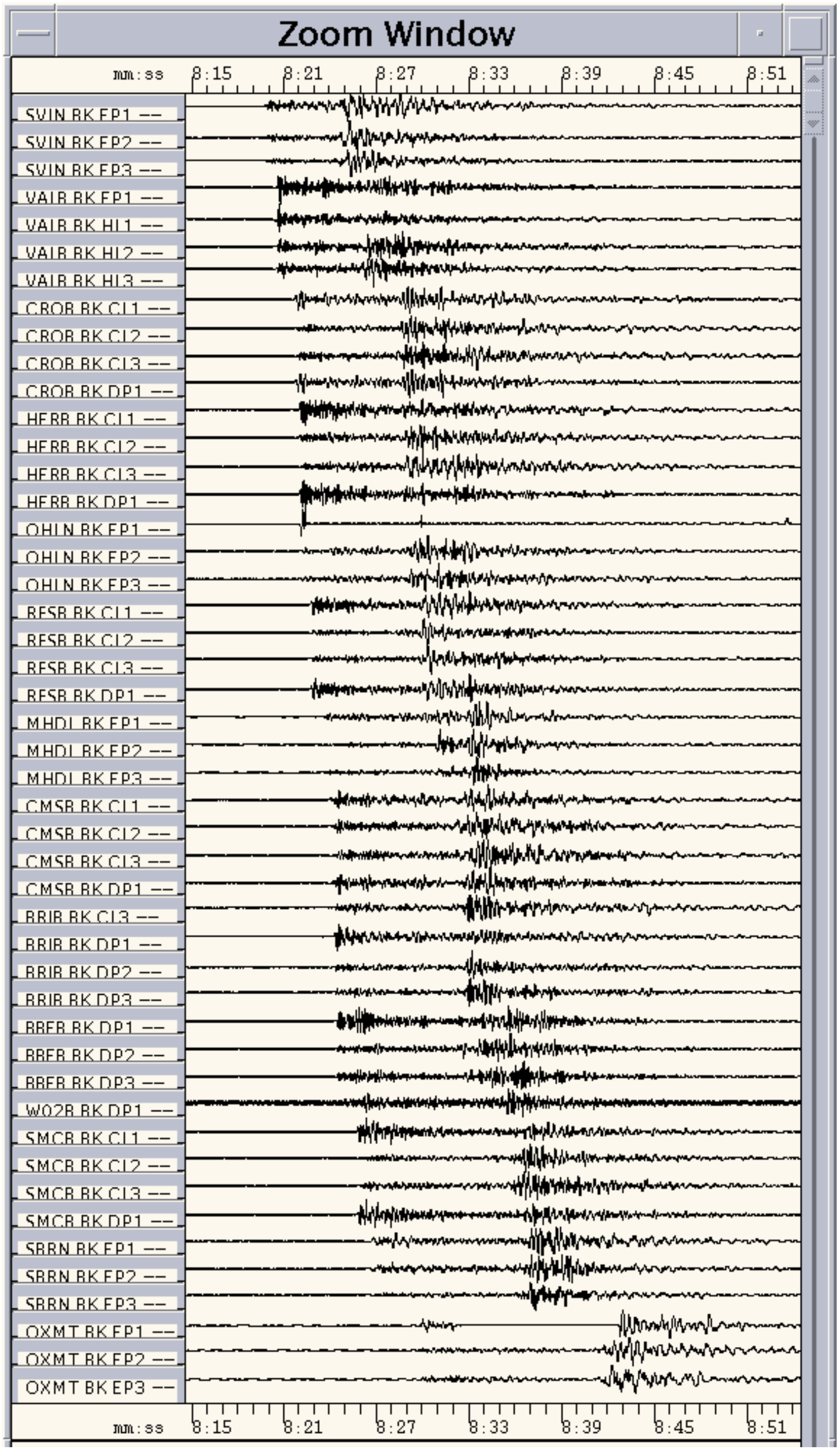

Figure 4. Record section of NHFN data for a Ml 4.6 earthquake located about 60 km northwest of Berkeley. These raw waveform data are ordered by epicentral distance and are relatively scaled.