4 Parkfield Borehole Network (HRSN)

Introduction

The operation of the High Resolution Seismic Network (HRSN) at Parkfield, California began in 1987, as part of the United States Geological Survey (USGS) initiative known as the Parkfield Prediction Experiment (PPE) (Bakun and Lindh, 1985).

Figure 4.4.1 shows the location of the network stations, their relationship to the San Andreas fault, sites of significance from previous and ongoing experiments using the HRSN, clusters of repeating earthquakes being monitored by the network, nonvolcanic tremors recorded by the network and located using envelope alignment arrival-times and a migrating grid search location method (Uhrhammer et al., 2001), background seismicity occurring this year and the epicenters of the 1966 and 2004 M6 earthquakes that motivated much of the research. The HRSN has recorded exceptionally high-quality data, owing to its 13 closely-spaced three-component borehole sensors (generally emplaced in the extremely low attenuation and background noise environment at 200 to 300 m depth (Table 4.4.2), its high-frequency, wide bandwidth recordings (0-100 Hz; 250 sps), and its sensitivity to very low amplitude seismic signals (e.g., recording signals from micro-earthquakes and non-volcanic tremors with equivalent magnitudes below 0.0 M).

Several aspects of the Parkfield region make it ideal for the study of small earthquakes and nonvolcanic tremors and their relationship to tectonic processes and large earthquakes. These include the fact that the network spans the SAFOD (San Andreas Fault Observatory at Depth) experimental zone, the nucleation region of earlier repeating magnitude 6 events, a significant portion of the transition from locked to creeping behavior on the San Andreas fault, the availability of three-dimensional P and S velocity models (Michelinii and McEvilly, 1991; Thurber et al., 2006), a long-term HRSN repeating seismicity catalog (complete to very low magnitudes and that includes over half of the M6 seismic cycle), a well-defined and relatively simple fault segment, the existence of deep nonvolcanic tremor (NVT) activity, and a relatively homogeneous mode of seismic energy release as indicated by the earthquake source mechanisms (over 90% right-lateral strike-slip).

In recent years, these features have also spurred additional investment in seismic instrumentation in the area that greatly enhances the HRSN's utility, including the ongoing installation of the TremorScope array (funded by the Moore foundation) and NSF's EarthScope SAFOD and PBO stations.

In a series of journal articles and Ph.D. theses, the cumulative, often unexpected, results of research by UC Berkeley and others using HRSN data trace the evolution of a new and exciting picture of the San Andreas fault zone, and they are forcing new thinking on the dynamic processes and conditions within both the seismogenic (upper ~15 km depths) and sub-seismogenic layers (~15-35 km depths), where recently discovered nonvolcanic tremors are occurring.

Parkfield has also become the focus of a major component of NSF's EarthScope project known as the San Andreas Fault Observatory at Depth (SAFOD) (http://www.earthscope.org/observatories/safod). The SAFOD project is a comprehensive effort whose objectives include drilling into the hypocentral zone of repeating M ~2 earthquakes on the San Andreas Fault at a depth of about 3 km and establishing a multi-stage geophysical observatory in the immediate proximity of these events. The purpose of such an observatory is to carry out a comprehensive suite of down-hole measurements in order to study the physical and chemical conditions under which earthquakes nucleate and rupture (Hickman et al., 2004). In these efforts, the HRSN plays a vital support role by recording seismic data used to directly constrain seismic signals recorded in the SAFOD main hole and by recording seismic events in the surrounding region to provide information on the larger scale fault zone processes that give rise to any changes observed in the main hole.

HRSN Overview

Installation of the HRSN deep borehole sensors (200-300 m) initiated in late 1986, and recording of triggered 500 sps earthquake data began in 1987. The HRSN sensors are three-component geophones in a mutually orthogonal gimbaled package. This ensures that the sensor corresponding to channel DP1 is aligned vertically and that the others are aligned horizontally. The sensors are also cemented permanently in place, ensuring maximum repeatability of the sensors' responses to identical sources, and allowing for precise relative measurements with minimal need for corrections and assumptions associated with moving the sensors. Originally a 10-station network, fully operational by January 1988, the HRSN was expanded to 13 borehole stations in late July 2001, and the original recording systems (see previous BSL Annual Reports) were upgraded to 24-bit acquisition (Quanterra 730s) and 56K frame relay telemetry to UCB. As part of funding from the American Recovery and Reinvestment Act (ARRA), an additional replacement/upgrade of the Quanterra 730 acquisition systems to 24-bit BA-SALT acquisition systems was accomplished in 2010–2011 and allows for local site storage and later retrieval of data during periods of sporadic telemetry failures. Properties of the sensors are summarized in Table 4.4.3.

The three newest borehole stations (CCRB, LCCB, and SCYB) were added, with NSF support, at the northwest end of the network as part of the SAFOD project to improve resolution of the structure, kinematics, and monitoring capabilities in the SAFOD drill-path and target zones. Figure 4.4.1 illustrates the location of the drill site, as well as locations of repeating earthquakes and nonvolcanic tremors recorded by the HRSN.

The three new stations have a similar configuration to the original upgraded 10 station network and include an additional channel for electrical signals. Station descriptions and instrument properties are summarized in Tables 4.4.2 and 4.4.3. All the HRSN data loggers employ FIR filters and extract data at 250 Hz (causal) and 20 Hz (acausal) (Table 4.4.1).
The remoteness of the SAFOD drill site and supporting HRSN stations required an installation of an intermediate data collection point at Gastro Peak, with a microwave link to our CDF (California Department of Forestry) facility. There was also one station, RMNB, that was located on Gastro Peak that transmitted directly to the CDF and served as a repeater for station LCCB. Prior to June 2008, eight of the HRSN sites transmitted either directly to or through repeaters directly to the CDF. This included stations RMNB and LCCB. The other five sites transmitted to a router at Gastro Peak, where the data was aggregated and transmitted to the CDF. However, due to disproportionately increasing landowner fees for access to the Gastro Peak site, we reduced our dependence on that site in the summer and fall of 2008 (in cooperation with the USGS) by re-routing telemetry of five of the sites previously telemetered through Gastro Peak to an alternative site at Hogs Canyon (HOGS). This eliminated the Gastro Peak microwave link, but left station RMNB and its repeater for LCCB at the mercy/good-graces of the Gastro Peak landowner. Subsequent negotiations with the landowner stalled and it was decided that RMNB was to be closed. An alternative repeater path for LCCB was also identified and made operational.

Continuous 20 and 250 Hz data from all HRSN channels are recorded and telemetered to the USGS site at Carr Hill for automatic picking and inclusion into Northern California Seismic System (NCSS) processing. The waveform data are also telemetered over a dedicated T1 circuit to the USGS and the Northern California Earthquake Data Center (NCEDC) at UC Berkeley.
for archiving and for online access by the community. The HRSN system also generates autonomous station triggers and event associations that are also archived at the NCEDC.

The HRSN’s telemetry system provides remote access to the local site data acquisition systems for state of health monitoring and control, and the recent upgrade to BASALT acquisition systems allows for local storage and retrieval of the data during telemetry outages.

Another feature of the HRSN system that has been particularly useful both for routine maintenance and for pathology identification has been the Internet connectivity of the central site processing computer and the individual stations’ data acquisition systems. Through this connectivity, locally generated warning messages from the central site processor are sent directly to the BSL for evaluation by project personnel. If, upon these evaluations, more detailed information on the HRSN’s performance is required, additional information can also be remotely accessed from the central site processing computer and generally from the individual site data loggers as well. Analysis of this remotely acquired information has been useful for trouble shooting by allowing field personnel to schedule and plan the details of maintenance visits to Parkfield. The connectivity also allows for local site acquisition shutdowns and restarts and for remote implementation of data acquisition parameter changes when needed.

The network connectivity and seamless data flow to UC Berkeley also provide near-real-time monitoring capabilities that are useful for rapid evaluation of significant events as well as the network's general state of health.

For example, shown in Figure 5.4.2 are surface wave seismograms of the teleseismic $M_w$ 8.2 earthquake off the northern coast of Chile (Lat.: 19.610S; Lon.: 70.760E; depth 25 km) occurring on April 1, 2014 23:46:47 (UTC) recorded on the SP1 (vertical) channels of the 12 HRSN borehole stations in operation at the time. Station RMNB no longer records data due to landowner issues. The seismic data from the quake was telemetered to Berkeley and available for analysis by the Northern California Seismic System (NCSS) real-time/automated processing stream within a few seconds of being recorded by the HRSN.

This is also a good signal source for examining the relative responses of the BP borehole network station/components to seismic ground motion. In this case, the vertical channels for 10 of the 12 stations in the 0.1-0.5 Hz band appeared to be working well and with the proper polarities at the time of the earthquake. However, the vertical channel for FROB shows an anomaly, and it appears that the vertical channel for VARB did not record any signal from the earthquake. By rapidly generating such plots following large teleseismic events, quick assessment of the HRSN seismometer responses to real events is easily done and corrective measures implemented with relatively little delay.

**Data Flow**

**Initial Processing Scheme**

Continuous data streams on all HRSN components are recorded at 20 and 250 sps on disk locally on the BASALT data-logger systems and transmitted in near-real-time over the T1 circuit to the USGS at Menlo Park, CA, where they are integrated into the Northern California Seismic System (NCSS) real-time/automated processing stream. The data is also transmitted to the Berkeley Seismological Laboratory (BSL) for archiving at the NCEDC. This integration of HRSN data into the NCSS data flow has significantly increased the sensitivity of the NCSN catalog at lower magnitudes, effectively doubling the number of small earthquake detections in the Parkfield area and SAFOD zone.

Shortly after being collected and recorded to disk on the central site HRSN computer at the USGS Carr Hill facility, event triggers for the individual stations are determined, and a multi-station trigger association routine then processes the station triggers and generates a list of HRSN-specific potential earthquakes.

For each potential earthquake association, a unique event identification number (compatible with the NCEDC classification scheme) is also assigned. Prior to the San Simeon earthquake of December 22, 2003, 30 second waveform segments were then collected for all stations and components and saved to local disk as an event gather, and event gathers were then periodically telemetered to BSL and included directly into the NCEDC earthquake database (DBMS) for analysis and processing.

Because of its mandate to record very low amplitude seismic signals and microearthquakes in the Parkfield area, the HRSN was designed to operate at very high gain levels to enhance signal sensitivity. This comes at the expense of dynamic range for the larger events (above ~M3.0). The sensitivity to low amplitude signals is also enhanced by the placement of sensors in the low noise borehole environment (200-300 m depth) and by exhaustive efforts at knocking down extraneous noise sources that arise in each station’s electronics, grounding, power, and telemetry systems and from interference from anthropogenic noise sources near the stations. As a consequence of the network’s high sensitivity, the HRSN also records numerous outside signals from regional events and relatively distant and small amplitude nonvolcanic tremor events. For example, spot checks of aftershocks following the M 6.5 San Simeon earthquake of December 22, 2003 using continuous data and HRSN event detection listings revealed that the overwhelming majority of HRSN generated detec-
Following the San Simeon and Parkfield earthquakes vastly exceeded the HRSN’s capacity to process and telemeter both continuous and triggered event waveform data. To prevent the loss of seismic waveform coverage, processing of the triggered waveform data was discontinued to allow the telemetry and archival of the 20 and 250 sps continuous data to continue uninterrupted. Subsequent funding limitations have since precluded reactivation of the triggered event processing. Cataloging of associated event triggers from the modified REDI real-time system algorithm continues, however, and both the continuous waveform data and trigger times are telemetered to and archived at the NCEDC, for access by the research community.

Because funding to generate catalogs of local micro-events from the tens of thousands of San Simeon and Parkfield aftershocks was not forthcoming, major changes in our approach to cataloging events had to be implemented. For example, HRSN data flow has now been integrated into the NCSS automated event detection, picking, and catalog processing. In addition, we have implemented a high resolution cross-correlation (pattern matching) based procedure to automatically detect, pick, locate, double-difference relocate, and determine magnitudes for select similar and repeating earthquake families down to very low magnitudes (i.e., below -0.0 M.)

These new schemes are discussed in more detail in the activities section below under subsection “SOH using Similar and Repeating Events”.

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**Table 5.4.2: Stations of the Parkfield HRSN.** Each HRSN station is listed with its station code, network id, location, operation period, and site description. The latitude and longitude (in degrees) are given in the WGS84 reference frame. The surface elevation (in meters) is relative to mean sea level, and the depth to the sensor (in meters) below the surface is also given. Coordinates and station names for the three new SAFOD sites are given at the bottom. Notes, denoted with ‘*’: There are 2 entries for JCNB, which failed in February of 2008 and has been replaced with a post-hole installation with ARRA funds. There are 2 entries for VARB, whose recording from a deep failed sensor (failure in August, 2003) was changed to a shallower sensor. Recording of data from station RMNB ended in July of 2011, due to landowner issues.

<table>
<thead>
<tr>
<th>Site</th>
<th>Net</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Surf. (m)</th>
<th>Depth (m)</th>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>EADB</td>
<td>BP</td>
<td>35.89525</td>
<td>-120.42286</td>
<td>466</td>
<td>245</td>
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<td>FROB</td>
<td>BP</td>
<td>35.91078</td>
<td>-120.48722</td>
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<td>Froelich Ranch</td>
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<tr>
<td>GHIB</td>
<td>BP</td>
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<td>-120.34774</td>
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<tr>
<td>JCNB</td>
<td>BP</td>
<td>35.93911</td>
<td>-120.43083</td>
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<td>01/1987 - 02/18/2008</td>
<td>Joaquin Canyon North</td>
</tr>
<tr>
<td>JCNB*</td>
<td>BP</td>
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<td>-120.43083</td>
<td>527</td>
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<td>-120.47772</td>
<td>1165</td>
<td>73</td>
<td>01/1987 - 07/20/2011</td>
<td>Gastro Peak</td>
</tr>
<tr>
<td>SMNB</td>
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<td>-120.58009</td>
<td>699</td>
<td>282</td>
<td>01/1987 -</td>
<td>Stockdale Mountain</td>
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<tr>
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<td>-120.44707</td>
<td>478</td>
<td>572</td>
<td>01/1987 - 08/19/2003</td>
<td>Varian Well</td>
</tr>
<tr>
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<td>-120.44707</td>
<td>478</td>
<td>298</td>
<td>08/25/2003 -</td>
<td>Varian Well</td>
</tr>
<tr>
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<td>Little Cholame Creek</td>
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<td>-120.5366</td>
<td>945</td>
<td>252</td>
<td>08/2001</td>
<td>Stone Canyon</td>
</tr>
</tbody>
</table>

Notes:
- **EADB** to **SCYB**: These sites were chosen at the time of the 2003 Parkfield M6 earthquake for their instrumental quality and their detailed knowledge of the local geology and faulting.
- **S**: The depth to the sensor (in meters) below the surface is also given.
- **Notes**: Denoted with ‘*’: There are 2 entries for JCNB, which failed in February of 2008 and has been replaced with a post-hole installation with ARRA funds. There are 2 entries for VARB, whose recording from a deep failed sensor (failure in August, 2003) was changed to a shallower sensor. Recording of data from station RMNB ended in July of 2011, due to landowner issues.

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**Current Processing**

Since the beginning of the network’s data collection in 1987, and up until 2002, local and regional events were discriminated based on analyst assessment of S-P times, and only local events with S-P times less than ~2.5s at the first arriving station were picked and located as part of the HRSN routine catalog. However, because of the network’s extreme sensitivity to the large swarm of aftershocks from the 2003 San Simeon and 2004 Parkfield M6 earthquakes (e.g., in the first five months following the San Simeon mainshock, over 70,000 event detections were made by the HRSN system, compared to an average five month detection rate of 2500 prior to San Simeon) and because of ever declining funding levels, analyst review of individual microearthquakes was abandoned.

In addition, the dramatic increase in event detections following the San Simeon and Parkfield earthquakes vastly exceeded the HRSN’s capacity to process and telemeter both continuous and triggered event waveform data. To prevent the loss of seismic waveform coverage, processing of the triggered waveform data was discontinued to allow the telemetry and archival of the 20 and 250 sps continuous data to continue uninterrupted. Subsequent funding limitations have since precluded reactivation of the triggered event processing. Cataloging of associated event triggers from the modified REDI real-time system algorithm continues, however, and both the continuous waveform data and trigger times are telemetered to and archived at the NCEDC, for access by the research community.

Because funding to generate catalogs of local micro-events from the tens of thousands of San Simeon and Parkfield aftershocks was not forthcoming, major changes in our approach to cataloging events had to be implemented. For example, HRSN data flow has now been integrated into the NCSS automated event detection, picking, and catalog processing. In addition, we have implemented a high resolution cross-correlation (pattern matching) based procedure to automatically detect, pick, locate, double-difference relocate, and determine magnitudes for select similar and repeating earthquake families down to very low magnitudes (i.e., below -0.0 M.). These new schemes are discussed in more detail in the activities section below under subsection “SOH using Similar and Repeating Events”.
Table 5.4.3: Instrumentation of the Parkfield HRSN. Most HRSN sites have L22 sensors and were originally digitized with a RefTek 24 system. The WESCOMP recording system failed in mid-1998, and after an approximate three year hiatus the network was upgraded and recording was replaced with a new 4-channel system. The new system, recording since July 27, 2001, uses a Quanterra 730 4-channel acquisition. Three new stations were also added during the network upgrade period (bottom). In 2010-2011, with ARRA funding, additional replacement/upgrade to 24-bit BASALT acquisition with station-local data storage took place. Notes, denoted with ‘*:’ There are 2 entries for JCNB, which failed in February of 2008 and has replaced with a post-hole installation with ARRA funds. There are 2 entries for VARB, whose recording from a deep failed sensor (failure in August, 2003) was changed to a shallower sensor. Recording of data from station RMNB ended in July of 2011, due to landowner issues.

2013–2014 Activities

In addition to routine operations and maintenance, project activities this year include: a) Presentation to the National Earthquake Prediction Evaluation Council (NEPEC) on the state of research and monitoring at Parkfield using the HRSN, b) Further development and implementation of HRSN state of health (SOH) monitoring using repeating events, c) Routine monitoring of non-volcanic tremor activity in the Parkfield-Cholame area and routine updates of the web-page on tremor activity in support of the TremorScope project, and d) Continued support of SAFOD activities with updates of the repeating and similar event seismicity catalog.

Routine Operations and Maintenance

Routine maintenance tasks required this year to keep the HRSN in operation include replacement of aging with new preamplifier units and testing/confirmation of the new design’s performance, cleaning and replacing corroded electrical connections, grounding adjustments, cleaning solar panels, testing and replacing failing batteries, ventilating battery and data logger housings to address problems with low power during hot weather, and repairing and realigning repeater sites and antennas.

Remote monitoring of the network’s health using the Berkeley Seismological Laboratory’s internally developed tools and SeisNetWatch software is also performed to identify both problems that can be resolved over the Internet (e.g., rebooting of data acquisition systems due to clock lockups) and more serious problems requiring field visits. Over the years, such efforts have paid off handsomely by providing exceptionally low noise recordings of low amplitude seismic signals produced by microearthquakes (below 0.0M,) and nonvolcanic tremors.

The network connectivity over the T1 circuit also allows remote monitoring of various measures of the state of health (SOH) of the network in near-real-time using waveforms directly. For example, background noise levels can be rapidly evaluated. We have developed and implemented an automated estimation of the power spectral density (PSD) distributions of background noise for all recorded HRSN channels and have developed summary PSD plots of these estimations to promote rapid evaluation of the noise levels through time. Shown in Figure 5.4.3 are power spectral density (PSD) plots of background noise for the 12 vertical HRSN channels in operation during 2013 for the 2-8 Hz frequency band where strong tremor signals are typically recorded. Continuous automated updating of such data plots in a variety of bands allow BSL personnel to rapidly evaluate changes in the network’s station response to seismic signals across the wide band high frequency spectrum of the borehole HRSN sensors. Changes in the responses often indicate problems with
the power, telemetry, or acquisition systems, or with changing conditions in the vicinity of station installations that are adversely affecting the quality of the recorded seismograms. Once state of health issues are identified, further remote tests can be made to more specifically determine probable causes, and corrective measures are then planned in advance of field deployment within a relatively short period of time.

**Presentation to NEPEC**

In a cost cutting effort, the USGS asked the National Earthquake Prediction Evaluation Council (NEPEC) this year to review the state of research and monitoring work around Parkfield, and to provide recommendations for future priorities. Roland Bürgmann and Robert Nadeau of the BSL were asked to attend the meeting, to provide a briefing on research and monitoring efforts in the area using HRSN data, to listen to other presentations on Parkfield area research and monitoring efforts, and to share in discussions on the relative importance and future possibilities of the various data collection and analysis efforts taking place in the area. While it was worrisome that this discussion, prompted by squeezed budgets within the USGS EHP program was even needed, the case for continued support for HRSN operations was relatively easy to make and a number of positive comments were made about the HRSN by the NEPEC members (e.g., "The HRSN has come out very high on the priority list" and "If anything ought to stay, it is the HRSN"). It seems likely, therefore, that funding for continued HRSN operations will survive this round of USGS budget prioritization.

**SOH using Similar and Repeating Events**

The increased microseismicity (thousands of events) resulting from the San Simeon M6.5 (SS) and Parkfield M6 (PF) events, the lack of funds available to process and catalog the increased number of microearthquakes, and the increased interest in using the microquakes in repeating earthquake and SAFOD research have required new thinking on how to detect and catalog microearthquakes recorded by the HRSN.

One action taken to help address this problem has been to integrate HRSN data streams into the NCSN event detection and automated cataloging process. This approach has been successful at detecting and locating a significantly greater number of microearthquakes over the previous NCSN detection and location rate, essentially doubling the number of events processed by the NCSN. However, the HRSN-sensitized NCSN catalog is still only catching about half the number of local events previously cataloged by the HRSN using the old, HRSN-centric processing approach. Furthermore, triggered waveforms for the additional small NCSN-processed events are often not reviewed by an analyst, nor do these smaller events often have NCSN magnitude determinations associated with them.

These limitations can severely hamper research efforts relying on the more numerous similar and characteristically repeating microevents (e.g., earthquake scaling studies, SAFOD related research, deep fault slip rate estimation, and the compilation of recurrence interval statistics for time-dependent earthquake forecast models). They also reduce the efficacy of using frequently recurring microevents as a tool for monitoring the network state-of-health (SOH).

To help overcome these limitations, we continued this year to implement our semi-automated similar-event cataloging scheme based on pattern matching (match filter) scans using cross-correlation of the continuous HRSN data. The method uses a library of reference event (pattern) waveforms, picks, locations, and magnitudes that have been accurately determined, to automatically detect, pick, locate, and determine magnitudes for events similar to the reference event with a level of accuracy and precision that only relative event analysis can bring.

The similar event detection is also remarkably insensitive to the magnitude of the reference event used, allowing similar microevents ranging over about three magnitude units to be fully cataloged using a single reference event, and it does a remarkably good job at discriminating and fully processing multiple superposed events.

Once a cluster of similar events has been processed, an additional level of resolution can then be achieved through the identification and classification of the subset of characteristically repeating microearthquakes (i.e., near identical earthquakes) occurring within the similar event family (Figure 5.4.4). The pattern scanning approach also ensures optimal completeness of repeating sequences owing to scans of the matching pattern through "all" available continuous data, which is critical for applications relying on recurrence interval information. For example, only about half of the magnitude 0.26 events shown in Figure 5.4.4 were picked up by the NCSN-HRSN integrated network.

Figure 5.4.4 also shows how stable the performance of channel DP1 on the borehole VCAB.BP has remained over the ~five year period shown. Due to station malfunctions or
However, there are on the order of 200 such sequences that can be possible approximately every 10 days on an automated basis. Hence, on average, evaluations of this type will typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences. Repeating sequences of this magnitude typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences. Hence, on average, evaluations of this type will typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences.

This can be carried out repeatedly through time as additional repeats are identified with time resolutions depending on the number of repeating sequences used and the frequency of their repeats. Repeating sequences of this magnitude typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences. Hence, on average, evaluations of this type can be possible approximately every 10 days on an automated basis. However, there are on the order of 200 such sequences known in the Parkfield area, and if one is willing to include even more frequently occurring similar but non-identical events into the equation, near-daily automated SOH analyses are a possibility.

Armed with this type of information, technicians and field engineers can quickly identify and address major problems. In addition to a visual assessment, the high similarity of the events lends itself to the application of differencing techniques in the time and frequency domains to automatically identify even subtle SOH issues. For other networks recording continuously in the Parkfield area (e.g., NCSN, BDSN/TremorScope) it is also a relatively simple process to extend the SOH analysis using characteristic repeating event signals recorded at their stations (See BDSN station RAMR example in Figure 5.4.5 of the BSL’s 2011–2012 annual report). Furthermore, numerous repeating and similar event sequences are also known to exist in the San Francisco Bay, San Juan Bautista and Mendocino Triple Junction areas, where continuous recording takes place. Hence, application of the repeating event SOH technique to these zones should also be feasible.

This year we have finished adapting our cataloging codes to take advantage of faster computing now available on LINUX based machines. We have expanded the library of reference event patterns and retroactively scanned these patterns through previously recorded and ongoing data to capture and catalog an ever growing body of similar and repeating earthquakes for research purposes, in support of SAFOD, and for SOH monitoring (including the use of repeaters to identify and correct problems associated with the recently activated TremorScope stations). We have also continued to revise and automate our SOH waveform displays for rapid evaluation of HRSN performance based on repeater waveforms and have begun development of additional automated processing and display schemes to include visualization of spectral characteristics to the repeating event SOH analyses.

**Tremor Monitoring and TremorScope**

The HRSN played an essential role in the initial discovery of nonvolcanic tremors (NVT) and associated Low Frequency Events (LFE) along the San Andreas Fault (SAF) below Cholame, CA (Nadeau and Dolenc, 2005; Shelly et al., 2009), and continues to play a vital role in ongoing NVT and LFE research. The Cholame tremors occupy a critical location between the smaller Parkfield (~M6) rupture zone and the adjacent and much larger Ft. Tejon (~M8) rupture zone along the SAF to the southeast (Figure 5.4.1). Because the time-varying nature of tremor activity is believed to reflect time-varying deep deformation and presumably episodes of accelerated stressing of faults (Guilhem and Nadeau, 2012), and because anomalous changes in Cholame area NVT activity preceded the 2004 Parkfield M6 earthquake (Nadeau and Guilhem, 2009; Shelly, 2009), and because tremor activity appears to be an ongoing process in the area (Guilhem and Nadeau, 2012) we are continuing to monitor the tremor activity observable by the HRSN to look for additional anomalous behavior that may signal an increased likelihood of another large SAF event in the region.

To date, over 3200 NVT bursts have been identified and

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<tr>
<th>Station</th>
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<td>MMNB</td>
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<td>SCYB</td>
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<td>CCRB</td>
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<td>LCCB</td>
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<td>LCCD</td>
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<td>MUNB</td>
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<td>SCNY</td>
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<td>VARN</td>
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<td>VCAE</td>
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Figure 5.4.3: 2013 summary plots of 250 sps vertical component (i.e., DP1 channel) background noise Power Spectral Density (PSD) levels for the 12 operating HRSN borehole stations in the strong tremor frequency band (2-8 Hz or period 0.125–0.5 s). The mean PSD (dB) ranking (lowest to highest) at 3 Hz obtained from all available 2013 data on these channels are:

- MMNB.BP.DP1 -166.636
- SCYB.BP.DP1 -163.456
- CCRB.BP.DP1 -161.935
- LCCB.BP.DP1 -159.035
- EADB.BP.DP1 -156.827
- GHIB.BP.DP1 -154.757
- JCSB.BP.DP1 -151.567
- VCAE.BP.DP1 -150.041
- VARN.BP.DP1 -149.134
- FROB.BP.DP1 -141.947
- JCSB.BP.DP1 -139.245
- SMNB.BP.DP1 -136.973

Note that failed station JCNB (failure in late 2007) has been reopened as a post-hole installation. The blue period for station MMNB between ~days 110 and 180 reflects a malfunction eventually found to be occurring in the aging pre-amplifier unit. The new pre-amplifier replacement was tested at MMNB first and eventually fixed the problem.

Human error during field maintenance, this would not necessarily have been the case. Because repeating events can generally be reliably identified using any combination of 4 of the HRSN’s 35 channels, assessment of the channel responses for channels not in the 4 channel combination can be carried out. This can be carried out repeatedly through time as additional repeats are identified with time resolutions depending on the number of repeating sequences used and the frequency of their repeats. Repeating sequences of this magnitude typically repeat every one to two years, and we are in the process of expanding our similar event monitoring capability to 61 of these sequences. Hence, on average, evaluations of this type can be possible approximately every 10 days on an automated basis. However, there are on the order of 200 such sequences known in the Parkfield area, and if one is willing to include even more frequently occurring similar but non-identical events into the equation, near-daily automated SOH analyses are a possibility.

Armed with this type of information, technicians and field engineers can quickly identify and address major problems. In addition to a visual assessment, the high similarity of the events lends itself to the application of differencing techniques in the time and frequency domains to automatically identify even subtle SOH issues. For other networks recording continuously in the Parkfield area (e.g., NCSN, BDSN/TremorScope) it is also a relatively simple process to extend the SOH analysis using characteristic repeating event signals recorded at their stations (See BDSN station RAMR example in Figure 5.4.5 of the BSL’s 2011–2012 annual report). Furthermore, numerous repeating and similar event sequences are also known to exist in the San Francisco Bay, San Juan Bautista and Mendocino Triple Junction areas, where continuous recording takes place. Hence, application of the repeating event SOH technique to these zones should also be feasible.

This year we have finished adapting our cataloging codes to take advantage of faster computing now available on LINUX based machines. We have expanded the library of reference event patterns and retroactively scanned these patterns through previously recorded and ongoing data to capture and catalog an ever growing body of similar and repeating earthquakes for research purposes, in support of SAFOD, and for SOH monitoring (including the use of repeaters to identify and correct problems associated with the recently activated TremorScope stations). We have also continued to revise and automate our SOH waveform displays for rapid evaluation of HRSN performance based on repeater waveforms and have begun development of additional automated processing and display schemes to include visualization of spectral characteristics to the repeating event SOH analyses.
Figure 5.4.4: The ten most recent repeats of a characteristic sequence of repeating magnitude 0.26 ($M_p$, USGS preferred magnitude) microearthquakes recorded by vertical (DP1) channel of HRSN station VCAB. This sequence has repeated 50 times since the initiation of HRSN recording in 1987. Characteristically repeating microevents are extremely similar in waveform (typically 0.95 cross-correlation or better). High-precision relative location and magnitude estimates of these events show they are also nearly collocated (to within 5-10 m) and have essentially the same magnitude (+/- 0.13 $M_p$ units, among all sequences studied). Immediately following the Parkfield $M_6$ mainshock on Sept. 28, 2004, the frequency of repetition was greatly accelerated due to post-seismic loading from the mainshock (e.g., seven repeats in the three months following the mainshock). As time passes, however, the post-seismic effects from the mainshock have gradually diminished, repeating about two times a year.

In the BSL annual reports for 2010–2011, 2011–2012 and 2012–2013 we noted that the recurrence intervals (i.e., times between events in the repeating sequence) for events in this sequence were on the order of six to eight months. Based on this we predicted in the 2010–2011 report that the next repeat of the sequence would take place sometime in May through July of 2011. The occurrence of the July 18, 2011 event (blue/black) proved our prediction to be correct, and a subsequent repeat on January 25, 2012 (brown/dark-gray) also followed the six to eight month recurrence pattern. Another prediction was made in the following 2011–2012 annual report where we predicted at least one and possibly two additional repeats within the next year, with the next repeat expected in July through September of 2012. These predictions were also fulfilled with the occurrence of the September 15, 2012 (blue/black) and March 13, 2013 (brown/dark-gray) events. Again in the 2012–2013 annual report we predicted once again that at least one and possibly two more additional repeats would occur within the next year, with the next repeat expected in May through July of 2013. These predictions were also fulfilled with the occurrence of the November 16, 2013 (blue/black) event. The dashed line labeled “NEXT” serves to illustrate our expectation that events in this sequences will continue the repeat pattern. Because the recent recurrence intervals continue to range between about six to eight months, we again predict at least one and possibly two additional repeats within the next year, with the next repeat expected to occur sometime in May through July of 2014. The most recent search period for repeats at the time of this writing went through April 7 of 2014, with no subsequent repeat yet expected nor observed.

For network operational purposes, the repeating behavior of this and other sequences in the Parkfield area allows us to use repeating sequences to monitor changes in channel response relative to past performance and to rapidly identify and correct state-of-health (SOH) issues with real, naturally occurring signals. Making future predictions for such frequently repeating events and testing the prediction using real earthquakes could also be a useful motivating tool for teaching about earthquakes in an educational setting.
cataloged, and regular updates of the NVT catalog continue on an ~biweekly basis. Over the last year we have also developed a website displaying a map and section of recent 90-day tremor activity as well as a complete list of detected Parkfield-Cholame area tremor from July of 2001. This can be downloaded by researchers and the public at http://seismo.berkeley.edu/research/recent_tremor.html.

Efforts in Support of SAFOD

An intensive and ongoing effort by the EarthScope component called SAFOD (San Andreas Fault Observatory at Depth) was undertaken to drill through, sample, and monitor the active San Andreas Fault at seismogenic depths and in very close proximity (within a few tens of meters or less) to a repeating magnitude 2 earthquake site. The HRSN data play a key role in these efforts by providing azimuthal coverage of low noise and high sensitivity seismic waveforms from active and passive sources in the SAFOD region, by providing a backbone catalog of very small similar and repeating earthquakes detections, and by recording and archiving continuous waveform data.

As of early September 2007, SAFOD drilling had penetrated the fault near the HI repeating target sequence and collected core samples in the fault region that presumably creeps and surrounds the repeatedly rupturing HI patch. Unfortunately, due to complications during drilling, penetration and sampling of the fault patch involved in repeating rupture was not possible, though core sampling and installation of seismic instrumentation in the region adjacent to the repeating patch was achieved. Current efforts are focused on analysis of co-

Figure 5.4.5: Repeating earthquake data illustrating their utility for identifying problematic channel responses. Here a repeat of EarthScope’s SAFOD SF sequence (≈M2.1) occurring on August 09, 2013 was identified using HRSN stations. The event and its previous repeats were used to evaluate the performance of stations from the HRSN and other networks out to distances greater than 50 km from the HRSN. Shown are the last four SF sequence events recorded on the DP3 horizontal channel of Berkeley’s HRSN station EADB with no filtering. EADB is 16 km from the repeating events. From top to bottom, the events occurred on 11/02/2006, 12/20/2008, 11/23/2010, 05/30/2007, and 08/09/2013, respectively. Waveforms for the first three events are well recorded and consistent, indicating healthy station response. However, for the most recent event a significant degradation in response is seen. Signal from the 2013 event is contaminated with spiking about every second (indicative of solar charger issues) and a background noise buzz with an ~ white spectrum is superposed on the earthquake signal. Corrective action taken was to ensure proper grounding of the electronic components at the installation and to replace the datalogger.
lected core samples and long-term monitoring of the ongoing chemical, physical, seismological, and deformational properties in the zone (in particular any signals associated with subsequent repeats of the SAFOD target sequences).

HRSN activities this year have contributed in three principal ways to these and longer-term SAFOD monitoring efforts:

1) Processing of integrated HRSN and USGS data streams in the Parkfield area continues, effectively doubling the number of small events available for monitoring seismicity in the SAFOD target zone and for constraining relative locations of the ongoing seismic activity.

2) Telemetry of all HRSN channels (both 20 and 250sp/s data streams) continues to flow directly from Parkfield, through the USGS Parkfield T1 and the Northern California Earthquake Management Center (NCEMC) T1, to the USGS and the BSL for near real-time processing, catalog processing, and data archiving at the Web-accessible NCEDC Portal. This also provides near-real-time access to the HRSN data for the SAFOD community, without the week- or month-long delay associated with the previous procedure of having to transport DLT tapes to Berkeley to upload and quality check the data.

3) Continued monitoring and expansion of our repeating (characteristic and similar event sequences) earthquake catalog, with particular focus on expansion and refinement of repeating event data within the 1.5 cubic km volume centered on the SAFOD target zone. In 2012–2013, we expanded the number of repeating sequence reference patterns in this zone from 3 to 18 and cataloged (detected, double-difference relocated, and determined magnitudes for) repeating and similar events associated with these sequences. This year we have continued to update the sequences with ongoing similar and repeated events, resulting in an expansion of the number of earthquakes within this small SAFOD focused volume to over 1,300 unique microquakes. The pattern matching approach to detection is prone to identifying the same event from more than one reference earthquake, so a procedure was also developed to remove redundant events from the overall catalog. A procedure was also developed to integrate arrival time information from the redundant pattern matches to improve connectivity of events from different similar event sequences in the double-difference relocations.

Continued monitoring of the 18 sequences in the immediate SAFOD zone this year has also led to the identification of the next repeats of the SAFOD SF and LA sequences which both occurred on August 09, 2013. The apparent triggering within less than a day of the repeat of the LA sequence by the repeat of the SF sequence reflects the first evidence of a return of this triggering relationship since its disruption at the time of the 2004 Parkfield M6 mainshock.

Figure 5.4.5 shows recordings of the horizontal (DP3) channel from HRSN station EADB for the most recent (bottom) and three previous repeats of the SAFOD SF sequence. While the repeated nature of these events is clearly apparent in the waveforms, it is also clear that the quality of the recording of the most recent event is below standard. Waveforms recorded on most other HRSN channels do not show the high frequency lower amplitude buzz and spiking apparent on the EADB DP3 channel. Replacement of the old preamp with the new preamp design in the spring of 2014 has rectified the problem. While degradation of the signal is apparent visually, such degradation is not generally apparent from automated quality control checks of station performance. This illustrates, then, the additional benefit of visual inspection and comparison of repeating events in SOH evaluations.

Acknowledgments

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