High-Resolution and Controlled-Source Monitoring at Parkfield

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TECHNICAL ABSTRACT

A high-quality borehole seismometer network in place at Parkfield has produced unique earthquake and controlled-source (Vibroseis) data sets. In a series of journal articles and Ph. D. theses since 1991 we have presented the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate-boundary loading. Compelling evidence exists for changes with time both in seismicity and in wave propagation (from microearthquakes and from the vibrator) that appear to be coupled, and the region of the fault zone involved is the presumed nucleation volume SE from Middle Mountain. Synchronous changes well above noise levels have been seen among several parameters including seismicity rate, average focal depth, S-wave coda velocities, characteristic sequence recurrence intervals, fault creep and water levels in monitoring wells. The same data demonstrate conclusively the existence of an extremely regular and localized process of ongoing earthquake-accommodated slip in the fault zone. Plausible assumptions lead to estimates for the spatial distribution of variations in slip-rate on the fault surface from changes in recurrence of these 2000+ characteristic microearthquakes. We do not (yet) know the relationship of these variations to the M6

nucleation process but the unique findings so far have significant implications for source dynamics, for earthquake forecasting, and for scaling relations among source parameters such as fault slip, rupture dimension, stress drop and seismic moment. If this phenomenon is found through other high-resolution studies to be generally common behavior in active faults, we have the basis for a new method to monitor the changing strain field throughout the seismogenic zone. There now is a unique baseline of fault-zone behavior with distinct features based on hard observations rather than on theories, one that must be incorporated in developing new models for fault-zone deformation. That unique baseline was interrupted late in 1998 when the 1980s-vintage hardware finally recorded its last microearthquake and failed irreparably, as predicted in recent proposals with pleas for upgrade funds. With generous emergency assistance from the IRIS/PASSCAL instrument pool, we brought the system online in a stopgap mode with RefTek recorders at reduced bandwidth, but sufficient to track the characteristic event sequences. Simultaneously, NEHRP funds were made available to begin the upgrade, and we have sufficient resources to purchase and install up to 7 of the 10 sites.

NON-TECHNICAL SUMMARY

Intensive monitoring at the Parkfield Earthquake Prediction Experiment site in central California, under the direction of Thomas V. McEvilly of the University of California, Berkeley. This research involved the operation and maintenance of the high-sensitivity network of seismographs in the area, the use of a large, truck-mounted vibrator to generate seismic waves to probe the subsurface along the fault zone on a regular schedule, and the analysis and archiving of the data acquired. The goal of the study is to better understand the earthquake process at the scale of meters and the nature of temporal variations in earthquake recurrence patterns in order to detect and identify possible anomalous precursors in microearthquake activity or in wave propagation to the expected magnitude 6 earthquake.

PROJECT OVERVIEW

Background

The data acquired in this experiment are unique and they are producing results that force a new look at some conventional concepts and models for earthquake occurrence and fault-zone dynamics.

This research began with NEHRP in 1986 as a proposed direct test with proven and modern technology of two hypotheses critical to our understanding of the physics of the earthquake process, implications for earthquake hazard reduction, and the possibilities for short-term earthquake prediction - major goals of the NEHRP:

1) That the earthquake nucleation process produces stress-driven perturbations in physical properties of the rocks in the incipient focal region that are measurable, and
2) That the nucleation process involves progressive and systematic failure that should be observable in the ultralow-magnitude microseismicity with high-resolution locations and source mechanisms.

In a series of journal articles and Ph. D. theses, listed below, we have presented the results of this effort. They trace the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate-boundary loading, and they are forcing new thinking on the dynamic processes and conditions within the fault zone at the sites of recurring small earthquakes. Analyses of the 11+ years of Parkfield monitoring data have revealed significant and unambiguous departures from stationarity both in the seismicity characteristics and in wave propagation details within the S-wave coda for paths within the presumed M6 nucleation zone where we also have found a high V_P/V_S anomaly at depth, and where the three M4.7-5.0 sequences occurred in 1992-94. Synchronous changes well above noise levels have also been seen among several independent parameters, including seismicity rates, average focal depth, S-wave coda velocities, characteristic sequence recurrence intervals, fault creep and water levels in monitoring wells. We have been able to localize the S-coda travel-time changes to the shallow part of the fault zone, to demonstrate with numerical modeling the likely role of fluids in the phenomenon, and to connect the changes in seismicity to slip-rate variations evident in other (strain, water level) monitored phenomena. Scaling laws have been developed from the Parkfield earthquakes that can be projected to fit earthquakes up to M6, and they predict unprecedented high stress drops and melting on the fault surface for the smallest events. Exhumed fault-zone rocks provide independent evidence for such condition. Recurrence interval variations in the characteristic event sequences (>60% of the microearthquake population) have been used to map fault slip rate at depth on the fault surface. Along the way in this exciting discovery process we have challenged the conventional 'constant stress drop' source model, affirmed characteristic earthquake occurrence and developed four-dimensional maps of fault-zone microearthquake processes at the unprecedented scale of a few meters. The significance of these findings lies in their apparent coupling and inter-relationships, from which models for fault-zone process can be fabricated and tested with time. The more general significance of the project is its production of a truly unique continuous baseline, at very high resolution, of both the microearthquake pathology and the subtle changes in wave propagation, providing to the seismological community an earthquake laboratory available nowhere else. This unique body of observations and analyses has also provided much of the impetus for Parkfield as the preferred site for deep drilling into an active seismogenic fault zone. Our major publications follow.

Parkfield publications

<u>Journal articles</u>

Daley, T.M. and T.V. McEvilly, Shear wave anisotropy in the Parkfield Varian Well VSP, Bull. Seism. Soc. Am., **80**, 857-869, 1990.

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Nadeau, R. M. and T. V. McEvilly, Seismological Studies at Parkfield V: Characteristic microearthquake sequences as fault-zone drilling targets, Bull. Seism. Soc. Am., **87**, 1463-1472, 1997.

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McEvilly, T.V. and E. Karageorgi, Enhanced observations with borehole seismographic networks: The Parkfield, California experiment, in *Proceedings of the 1st Workshop on the Development of a Multiborehole Observatory at the Gulf of Corinth*, ICDP Report, 1996/97, 1998.

Nadeau, R.M. and T.V. McEvilly , Fault slip rates at depth from recurrence intervals of repeating microearthquakes, Science (in press), 1999.

Korneev, V.A., T.V. McEvilly and E.D. Karageorgi, Seismological Studies at Parkfield VIII: Modeling the Observed Controlled-Source Waveform Changes, Bull. Seism. Soc. Am. (submitted), 1999.

Ellsworth, Matthews, Nadeau, Nishenko, Reasenberg and Simpson, A Physically-Based Earthquake Recurrence Model for Estimation of Long-Term Earthquake Probabilities, Geoph. Res. L. (submitted), 1999.

Wenk, H-R., L.R. Johnson and L. Ratschbacher, A Large Psuedotachalyte Zone in the Eastern Peninsular Ranges of California, Tectonophysics (submitted), 1999.

Sammis, C.G.,R.M. Nadeau and L.R. Johnson, How strong is an Asperity, J. Geoph. Res. (submitted), 1999.

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Ph. D. Theses

Michelini, A., Fault Zone Structure Determined Through the Analysis of Earthquake Arrival Times, 1991.

Foxall, W., Fault-Zone Heterogeneity as a Controlling Factor in the Dynamic Behavior of the San Andreas Fault in Central California, 1992.

Nadeau, R., Full-Waveform Studies of Elastic-Wave Propagation in the San Andreas Fault Zone at Parkfield as a Process-Monitoring Technique, 1995.

Johnson, P., Source Processes of Small Earthquakes, M 1-5: Studies of the San Andreas Fault at Parkfield and Long Valley Caldera, California, 1997.

The scientific output of the Parkfield project can be illustrated with excerpts from several of the papers that have recently been submitted and are now under review for publication.

Nadeau and McEvilly (1999) devised a method for estimating fault slip rate:
"… recurring highly similar microearthquakes at Parkfield, California provide a means for inferring slip rate throughout the active fault surface from the time intervals between sequence events. …an 11-year high-resolution microseismicity record revealed systematic spatial and temporal changes in the slip rate that were synchronous with earthquake activity and other independent indicators of fault-zone slip. ...the basis for a new method to monitor the changing strain field throughout the seismogenic fault zone, adding the depth dimension to conventional surface-constrained measurements of deformation."

Korneev et al. (1999) provide a quantitative model of the Vibroseis travel-time anomaly:
"… one element of the Parkfield, CA Prediction Experiment, the borehole seismographic network there was illuminated routinely by a large shear-wave Vibroseis from several source points… Clear and progressive travel-time changes of up to 50 msec were detected, most prominent in the S-wave coda, and localized to propagation paths through the fault zone southeast of Middle Mountain, the section of the fault where previous M6 earthquakes have initiated. We model the observations successfully as interaction (reflection and transmission) of the shallow wavefield with a 200-meter-wide low-velocity fault zone in which the velocity increases by 6% due, we hypothesize, to hydrological changes accompanying a significant pulse in slip rate and seismicity."

Ellsworth et al. (1999), propose a new approach to earthquake probabilities:
" A physically-motivated model for earthquake recurrence based on the Brownian relaxation oscillator is introduced. ….. Application of this model to the next M 6 earthquake on the San Andreas fault at Parkfield, California suggests that the annual probability of the earthquake is between 1:10 and 1:13."

Sammis et al. (1999) use the Parkfield data in developing a fractal asperity model:
"…Nadeau and Johnson [1998] found that the smallest events occurred on patches having a linear dimension of the order of 0.5 m, displacements of about 2 cm, and stress drops of the order of 2000 MPa, roughly 10 times larger than rock strengths measured in the laboratory. … A hierarchical fractal asperity model is presented, which is based on recent laboratory observations of contact distributions in sliding friction experiments. …. The spatial distribution of hypocenters in the Parkfield area is shown to be consistent with this simple fractal model and with a hierarchical clustering of asperities having a fractal dimension of D = 1 and discrete resealing factor of about 20."
Wenk et al. (1999) see evidence in psuedotachylites for faulting processes inferred from Parkfield microearthquakes

"…The pseudotachylites formed during a late brittle event (56-62 My) and postdated the large ductile mylonitic deformation in the Santa Rosa mylonite zone (65-87 My) as ascertained by 4OAr/39Ar ages. … From the sizes, energies required for melting estimated to range between 105 J for smaller veins and 1010 J for larger ones. Interestingly the energy distribution and geometry of these pseudotachylites corresponds closely to energy distributions of current microseismic events along the San Andreas fault at Parkfield, suggesting that basic mechanisms may be similar and due to intrinsic mechanical properties of rocks."

The significance of past, ongoing and proposed continuing research at Parkfield is wide-ranging in shaping a new understanding of fault-zone process at the scale of meters (M,<0). Implications affect our thinking on source dimensions, temperature, stress drop, triggering, temporal changes and earthquake probability models. These contributions have been possible because of the unique nature of this data set -- borehole sensors in a quiet region giving a large magnitude range of on-scale recordings with high signal-to-noise ratio and minimum near-surface site effects, coupled with the clustered nature of the seismicity -- make it ideal for studies fault zone dynamics and for seeking evidence of identifiable precursory phenomena prior to large earthquakes. Arguably the Parkfield experiment is the most significant and perhaps the only effort that will ultimately provide a definitive answer to the precursor question.

A recently added compliment to this project lies in the planned deep drilling experiment in the Parkfield study area (NW from Middle Mountain). The site was selected largely because of the wealth of information the Parkfield experiment has provided on the fault zone. The target fault surface is the location of a group of characteristic event clusters, one or more of which will be selected for penetration. This ambitious exercise in precision drilling and hypocenter location requires functionality of the borehole network - in fact, we hope to install two more borehole stations in the vicinity of the drilling site.

RESEARCH SUMMARY

History

A high-resolution seismographic network (HRSN) for the Middle Mountain stretch of the San Andreas fault zone, where the M6 event is presumably nucleating, was installed in boreholes beginning in 1986. In November 1987, the Varian well vertical array was installed and the first VSP survey was conducted, revealing clear S-wave anisotropy in the fault zone. During 1988, the network was completed to ten 3-component 500 sps radio-telemetered stations, incorporating a deep (572 m) sensor in the Varian well string into the network. The Varian system was slaved in 1988, for about two years, to the Vibroseis control signals, allowing simultaneous recording of vibrator signals on both systems. In 1991, low-gain event recorders (from PASSCAL) were installed to extend the dynamic range to M_L about 4.5. In 1991, we determined a local 3-D velocity model by joint inversion, and data reduction methods were designed to handle the massive data sets in a monitoring mode. Since 1989, new analysis techniques gradually have been developed to extract and display the information contained in the high-resolution data from both Vibroseis and microearthquakes to support a variety of research efforts in the project. The daunting technical and data processing requirements for this project were met only through the participation of several graduate students and technical personnel at the Lawrence Berkeley National Laboratory Center for Computational Seismology and Geophysical Measurements Facility.

The data acquisition system that gave up the ghost in 1998 was a modified VSP system using a 1980-vintage LSI-11 cpu and a 5 MByte removable Bernoulli system disk with a 9-track tape drive, configured to record both triggered microearthquake and Vibroseis (discontinued in 1997) data. The system was remote and completely autonomous - we cannot monitor its status from Berkeley - so that reliability and hands-off operation was a crucial design feature. Recent grants reduced field support to quarterly maintenance visits - a fatal error.

The system has recorded more than 10000 microearthquakes in the Parkfield region along with many times that number of regional and teleseismic events. More than 5000 good quality 3-D locations make up the catalog for the 40 km stretch of the fault zone centered at Middle Mountain. More than 50 controlled-source data sets from the Vibroseis monitoring program have also been gathered from mid-1987 until its termination in 1997.

This project traditionally supported, in addition to the research elements, the basic field operation and maintenance effort, the associated routine data reduction tasks, the generation of the high-resolution location catalog and the archival tasks for the catalog and waveforms – and recently, the complete system replacement. Supplementary funding from USGS began the upgrade of the system and the labor intensive exercise of temporarily running the network on individual portable instruments in continuous record mode.

Replacing the acquisition system

The data acquisition system operated quite reliably until late 1996, when periods of unacceptably high downtime ensued, with as many as 7 of the remote, solar-powered telemetered stations down due to marginal solar generation capacity and old batteries, and recording system outages of a week or more became common. In 1998 it failed for good.

Thanks to emergency funding from NEHRP, we began to replace the present system with a modern 24-bit acquisition system, and resources requested in this proposal will complete the upgrade of the 10 stations. The new system is compatible with the data flow and archiving common to all the elements of the Berkeley Digital Seismic network (BDSN) and data center (NCEDC). This will provide remote access and control of the system and produce data with better timing accuracy and longer records flowing seamlessly into NCEDC. We had a one-sample timing uncertainty, and a record length limitation because the time to do a tape write after event detection is longer than the length of the record, and we were off-line for the write time. The new system, based on the Quanterra 730, solves all three problems: timing resolution, dynamic range, and complete detection, in addition to the advantage in the conventional data flow. Funds for completing the upgrade are included in the first year budget. Year two is devoted to the research effort.

Research highlights

Fault-zone dynamics. About two-thirds of all the Parkfield earthquakes are members of a few hundred sequences of as many as 20 or more characteristic events - regularly recurring earthquakes so similar that waveform coherency exceeds 0.98 over a 50Hz+ bandwidth for the entire wavetrain, and relative hypocenter locations differ only by 5-10 meters, near the resolution of our analysis. This phenomenon may be common to creeping seismogenic fault zones in general, but there are not the high-resolution networks in place to test this at the $-1<M<2$ level where recurrence times are less than a

few years. Nadeau and McEvilly, 1997, illustrated the typical spatio-temporal features of the characteristic sequences, and the high resolution + high sensitivity required to fully expose their existence at the low magnitudes where the process is visible in a few years' data. This new view of fault-zone process is fundamental to our research program, and we need to complete the characterization of the microseismicity throughout the fault zone and up to the present time. We also extended the characterization of fault seismicity to the entire creeping part of the full San Andreas system. 'Characteristic' implies more than just 'similar', a criterion easily satisfied by nearby events when observed at lower bandwidth. We explored the apparent relationship of recurrence interval and fault slip rate in Nadeau and McEvilly (1999).
There are immediate consequences of characteristic recurrence. One striking implication follows from the near-constant moment release rate in a sequence. If we can independently estimate the associated slip rate on the fault at the sequence, an entirely new approach to source parameter estimation is possible, as detailed in Nadeau and Johnson (1998). They demonstrated a scheme for estimating the slip surface area that is independent of spectral corners. Furthermore, they derived a set of scaling relations among moment, area, slip and stress drop that seem to hold for the range $0<M<6$ on the San Andreas fault in central California. An inescapable result is a strong moment dependence for stress drop, with kilobar+ values implied for the small events. There is supporting petrological evidence in exhumed fault zones for these extreme hypocentral conditions (Wenk et al., 1999).

Systematic changes in recurrence intervals are seen in some sequences, equivalent to changes in moment release rates. From the relationships of Nadeau and Johnson (1998), this implies change in slip rate. The characteristic sequences thus become strain meters within the fault zone. We have begun to use this idea to map the changing slip rate throughout the fault zone (Nadeau and McEvilly, 1999). Spatially averaged deviation of derived slip rates from sequence means were used to present annual fractional variations, and these data are generally consistent with changes expected to accompany the 10/92-12/94 M4.5+ major earthquake sequences, There is good correlation of recurrence-derived slip rates with surface-based measurements of deformation.

The highly structured seismicity at Parkfield stands in stark contrast to the much less organized picture of earthquake rupture and fault deformation painted by conventional lower resolution data sets. When high-resolution data are processed using advanced techniques, the appearance of diffuse uncorrelated seismicity largely resolves itself into an organized pattern of repeating earthquake groups having the same size, location, waveforms and constant recurrence interval. In addition, the hypocenters of most earthquakes become restricted to a narrow planar core of seismic strain release within which the repeating earthquake sites cluster on several scales -- clusters of clusters. Fractal analyses of the highly resolved hypocenters show a considerably lower fractal dimension, ($D \sim 1$), than that observed and predicted for Parkfield based lower resolution data (typically, $D = 2$ to 3). In addition, as shown by Sammis et al. (1999), the fractal pair-correlation function shows discrete behavior (undulations) indicating a strong heterogeneity in the spatial distribution of earthquakes on the SAF at Parkfield. This discrete behavior is masked, however, by uncertainties in location when less well resolved catalogs such as NCSN are used.

Fault-zone guided waves. There has been a lot made of so-called fault-zone guided waves (FZGW). Much of it has been directed toward modeling wave propagation in relatively simple, vertical low-velocity structures in order to match discrete observations of the late, low frequency arrivals sometimes recorded near the fault trace (Vidale and McEvilly, 1999). We began to explore this problem from a somewhat different approach, using the extensive observations of these waves in the Parkfield network, the 3-D P- and S-velocity model for the fault zone, and our Vibroseis results that place an apparent strain-related zone of changing wave propagation parameters within the shallow (the upper 3 km) part of the fault zone (Karageorgi et al., 1997). In this two-fold investigation we characterized the distribution throughout the fault zone of source-receiver paths that produce strong FZGW signals from earthquakes. The goal of this part of our research was to be able to first determine the patterns of generation and propagation of FZGW, to characterize the wavefield in terms of velocity and particle motion relative to the fault zone, and finally, to model the phenomenon numerically using new 3-D guided-wave algorithms under development. Our initial work on this suggested that the strong generation as well as the wave propagation is a shallow feature of the fault zone.

The Vibroseis monitoring investigation reported significant travel-time changes in the coda of S for paths crossing the fault zone southeast from the epicenter of the 1966 M6 earthquake. Progressively decreasing travel times in the anomalous region reached 50 msec or more by the end of the study. Changes in frequency content and polarization were also found and those effects, too, could be localized to the zone of common nucleation and rupture onset for the previous M6 earthquakes, and, possibly, the region of slip initiation for the great earthquake of 1857. The temporal pattern in these variations appears to be synchronous with changes in deformation and seismicity measured independently (Nadeau and McEvilly, 1999). Because similar variations are not seen in the waveforms recorded from microearthquakes in the same part of the fault, Karageorgi et al. (1997) conclude that changing fluid conditions in the uppermost section of the fault zone in response to deeper, tectonic stress perturbations are the likely cause of the temporal variations. Korneev and McEvilly (1999) modeled the variations numerically and successfully explained the observations as interaction (reflection and transmission) of the shallow wavefield with a 200-meter-wide low-velocity fault zone in which the velocity increases by 6% due, we hypothesize, to hydrological changes accompanying a significant pulse in slip rate and seismicity that was evident in independent data.