Focused Observation of the San Andreas/Calaveras Fault intersection in the region of San Juan Bautista, California

Clifford Thurber, Dept. of Geology and Geophysics, Univ. Wisconsin-Madison
Mick Gladwin, C.S.I.R.O. Exploration & Mining, Queensland, Australia
Allan Rubin, Dept. of Geosciences, Princeton University, NJ
D. Charles DeMets, Dept. of Geology and Geophysics, Univ. Wisconsin-Madison

BACKGROUND

We propose instrumentation of the San Juan Bautista (SJB) region in a 50 x 20 km area covering the transition region of the San Andreas/Calaveras fault system, with a total of 25 borehole strain sites (some including downhole seismometers), plus surface seismic/strong motion instruments and continuous and campaign GPS. The array will provide a characterization of (1) the spatial distribution of seismic and aseismic slip in the area and (2) the relationship between seismic and aseismic slip and repeating microearthquake sequences (fault "streaks").

The SJB region of the San Andreas fault (SAF) is a transition zone between the creeping section to the southeast and the "locked" section to the northwest. The former section is slipping aseismically with a surface long-term creep rate comparable to the rate of lateral movement between adjacent crustal blocks of 35 mm per year, and the latter section was the southernmost extent of rupture during the 1906 San Francisco earthquake.

There have been a number of geodetic and seismic studies in this region over the past few decades. Geodetic surveys of a 24 station trilateration network in this region from 1971 to 1978 by Savage et al. (1979) suggested that regional deformation could be roughly described by rigid body motion of three blocks, one to the northeast of the Calaveras fault, a central one bounded by the Calaveras and SAF, and a third to the southwest of the SAF, with accommodation occurring by right-lateral slip on the SAF of 13 mm/yr and 17 mm/yr on the Calaveras. The data from these surveys indicated that there was no significant accumulation of strain in the southwestern block, an accumulation of shear strain, with a maximum of 0.16 microstrain/yr right-lateral across a plane at N 61° W, and negligible dilatation in the eastern block, and an accumulation of shear strain, with a maximum of 0.33 microstrain/yr at N 53° W (close to the local strike of the Sargent fault), and dilatation of 0.33 microstrain/yr in the central block. Studies of surface creep observations from creepmeters operated since 1970 by the USGS in this region have indicated that surface creep consists of a steady state component with larger episodic creep episodes. There is some evidence of these creep events propagating along the fault, and stress transfer from nearby earthquakes has some influence on the medium term creep rate.

The southern section of the Calaveras fault has been characterized by seismic data as having a near-vertical seismically active fault coincident with its fault trace (Hill et al., 1990). The SAF in this region is characterized by steady background seismicity, and has experienced 15 earthquakes of magnitude greater than M= 4.5 between 1960 and 1999 (Uhrhammer et al., 1999). Recent P- and S-wave tomographic imaging of the SAF zone southeast of SJB (Thurber et al., 1997) found that (1) the main zone of seismicity along the SAF lies in the depth range of 3 to 7 km on a plane dipping about 70° SW; (2) all the seismically active zones lie within or on the edge of regions with Vp above 5 km/s; (3) zones of high Vp/Vs are adjacent to and/or overly the main seismically active zones. The latter finding provides strong evidence for the presence of fluids in the fault zone, but also leaves unanswered questions regarding the source of the fluids and the related question of the relationship between the fluid-rich zones and the seismicity. Accurate relative locations of microearthquakes in this region (Rubin et al., 1999) have identified microseismicity in highly concentrated streaks, aligned in the direction of slip and at typical depths of 4km to 8km. King and Nabelek (1985) have suggested the importance of fault bends in influencing tectonic development by limiting the extent of fault rupture, and the slight bend in the SAF fault to the immediate north of the SJB region may be significant in influencing the extent of earthquake rupture.

A small borehole strain array consisting of a Sacks-Evertson dilatometer at Searle Road (operated by USGS personnel) and a Gladwin Borehole Tensor Strainmeter (BTSM) near SJB was installed in 1982-83 and operated continually since that time (Figure 1, inset). The instruments are separated by 5 km, and the joint 15-year dataset has provided some critical observations of aseismic fault slip processes in the uppermost 5 km of the fault (Figure 1). These processes include

- a series of slow earthquakes in 1992, 1996 and 1998 (Figure 2) with adjacent slip surfaces and equivalent magnitudes of about M = 5; the lower boundaries of these slip surfaces are not well determined, but are likely to be near to the sources of microseismicity at depths of 4-8 km.
- significant temporal strain rate changes in the periods intervening between these slow earthquakes, and
- a series of episodic strain events caused by repeating slip on a small section of the fault at shallow depth.

SCIENCE GOALS

There are some key insights necessary for better understanding of earthquake processes on the SAF, which may be assisted by detailed study of this region.

Characterization of the relative significance of seismic and aseismic slip: One of the key questions to arise over the past decade, since some detailed strainmeter observations of the range and extent of aseismic slip episodes have been available, is - to what extent is aseismic slip, including post-seismic deformation and "slow earthquakes," a component of the stress relief process along a fault? The observations to date from the two borehole strainmeters near SJB suggest that aseismic slip processes may be of equivalent or greater magnitude than the associated seismic episodes. However it is essential to broaden the current array of instruments to determine if this is a more general finding applicable to other regions of the SAF.

Identification of processes limiting the extent of rupture of large earthquakes: What are the determining processes associated with limiting the extent of rupture of large earthquakes? The SJB region provides one of only two areas in the US where this question can be studied directly (the other being the Parkfield region). While there have been considerable seismic studies to date, the associated observations of response to stress have been relatively sparse, and a more detailed investigation of strain changes at periods from days to years should yield valuable insights.

Observation of slip and stress transfer around such a locked patch: There is an extensive literature of studies based on both surface creep observations, seismic studies and modeling, which have linked the strain accumulation around locked regions of a fault trace such as the SAF, to the occurrence of moderate sized earthquakes in these locations. The SJB region is a likely candidate to contain a locked portion of the fault, and one of our goals should be a more detailed understanding of the processes associated with slip and stress transfer around such a locked patch.

Investigation of aseismic fault processes associated with fault intersections: There are a considerable number of unresolved questions associated with fault geometry on earthquake preparation, rupture and stress transfer. For example, what are the effects of fault steps and fault bends on stress transfer processes? How does slip partitioning at a fault junction influence the stress transfer and thus triggering of earthquakes from one fault to another? The Calaveras/Sargent/SAF junction provides a good laboratory to investigate the detail of strains associated with stress transfer at both short and longer periods.

Identification of aseismic slip associated with repeating microearthquakes: Recent advances in precise relative location of microearthquakes have provided detail of seismicity partitioning on various sections of a fault surface previously unobtainable. In order to correlate the detail of the occurrence and propagation over time of these microearthquakes (Rubin & Gillard, 2000) with

aseismic slip at periods of days and months in adjacent portions of the fault surface, arrays of strainmeters and GPS sites will be necessary both along the fault, and at distances enabling resolution of processes at depths of 5-10km. It is intriguing that there is an apparent association of the identified microseismic lineations in this region with the slow earthquake slip surfaces. The December 1992 event (or its stress field) apparently "passed through" a seismogenic lineation near 4 km depth without producing a single earthquake, while producing abundant seismicity at 6 km depth (Figure). In fact, during the next 5 months the lineations near 6 km depth produced a typical "aftershock" sequence, while that at 4 km depth experienced its lowest seismicity rate since the 1989 Loma Prieta earthquake. The implication seems to be that either the (previously and subsequently) seismogenic zone at 4 km depth slipped aseismically during the 1992 event, or that the slow event occurred on a plane parallel to but offset from the seismogenic SAF. These results are important because the relationship between creep events, microseismicity, and large (seismic) earthquakes is very poorly understood; it is not even known if a natural fault surface can both nucleate earthquakes and creep aseismically. The depth extent of the slow earthquake slip surfaces is currently not well constrained, since the borehole instruments are only 1-2 km from the fault trace. More closely-spaced observations at distances of 3-10 km from the fault trace will provide much better constraints on the relationship of these slow slip events to microseismicity on the fault.
Investigation of the role of fluids in fault zone processes: The seismic tomography studies referred to above provide strong evidence for the presence of fluids in the fault zone, but also leaves unanswered questions regarding the source of the fluids and the related question of the relationship between the fluid-rich zones and the seismicity. Are the fluids leaking down into the fault zone from above, or are they generated in the seismically active zones and expelled upwards? The highest Vp/Vs zones are not directly adjacent to or overlapping the seismically active zones - does this mean the fluids are causing aseismic slip as opposed to enabling seismic slip? Both borehole strainmeter observations of aseismic slip, and magnetotelluric profiling may help shed some light on these questions.

INSTRUMENTATION

This proposal concentrates on deployment of borehole strainmeters and co-located seismic and GPS instrumentation in a 50 km regions around SJB. Borehole strainmeter arrays will provide detailed information on fault slip episodes at depths and scales equivalent to the array spacing. Along the SAF, an array of strainmeters located at 3 km from the fault trace, with 5 km spacing, will enable investigation of strain processes in the upper 5 km of the fault surface. Both sides of the fault trace should be instrumented, since material on the east side has a considerably lower seismic velocity, and thus elastic modulus, from the material to the west of the fault trace. Observations from both sides of the fault will enable unambiguous models of fault processes at depth. The close-instruments can be staggered on either side of the fault to gain maximum scientific benefit at minimum extra cost. Instruments spaced at 10-km intervals and a distance of 10 km from the fault trace will provide detail of larger scale and deeper processes. A further number of borehole sites in the region between the Calaveras and SAF, and to the northwest of the Calaveras, will complete the strainmeter array, with a suggested total of 25 instrumented sites. Combining the observations from strainmeter s with seismic/strong motion and GPS observations will provide superb detail on the full range of slip processes. Figure 4 illustrates the instrument layout.

REFERENCES

Hill, D. P., J. P. Eaton, and L. M. Jones, Seismicity, 1980-86, U.S. Geol. Surv. Prof. Pap. 1515, 115-151, 1990.

King, G. C. P., and J. Nabelek, Role of fault bends in the initiation and termination of earthquake rupture, Science, 228, 984-987, 1985.

Linde, A. T., M. T. Gladwin, M. J. S. Johnston, R. L. Gwyther, and R. G. Bilham, A slow earthquake sequence on the San Andreas fault, Nature, 383, 65-68, 1996.

Rubin, A. M., D. Gillard, and J.-L. Got, Streaks of microearthquakes along creeping faults, Nature, 400, 635-641, 1999.
Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Geodelite measurements of deformation near Hollister, California, 1971-1978, J. Geophys. Res., 84, 7599-7615, 1979.
Thurber, C., S. Roecker, W. Ellsworth, Y. Chen, W. Lutter, and R. Sessions, Two-dimensional seismic image of the San Andreas fault in the Northern Gabilan Range, central California: evidence for fluids in the fault zone, Geophys. Res. Lett., 24, 1591-1594, 1997.
Uhrhammer, R., L. S. Gee, M. Murray, D. Dreger, and B. Romanowicz, The Mw 5.1 San Juan Bautista, California earthquake of 12 August 1998, Seismol. Res. Lett., 70, 10-18, 1999.

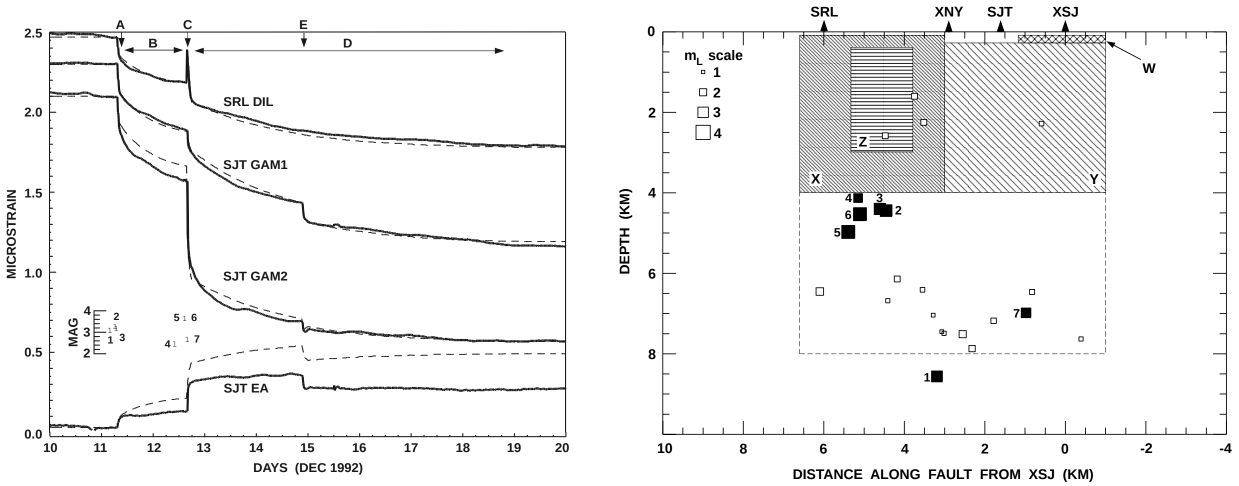

Figure 1. (a) Slow earthquake sequence of December 1992 observed at SJT tensor site and SRL dilatometer site approximately 5 km apart, and modeled strain resulting from aseismic slip. (b) A cross sectional area of the San Andreas fault trace in the vicinity of SJT and SRL. Aseismic slip on surfaces X,Y and Z is postulated by Linde et al. (1996) as responsible for the coseismic steps and aseismic strain relief observed.

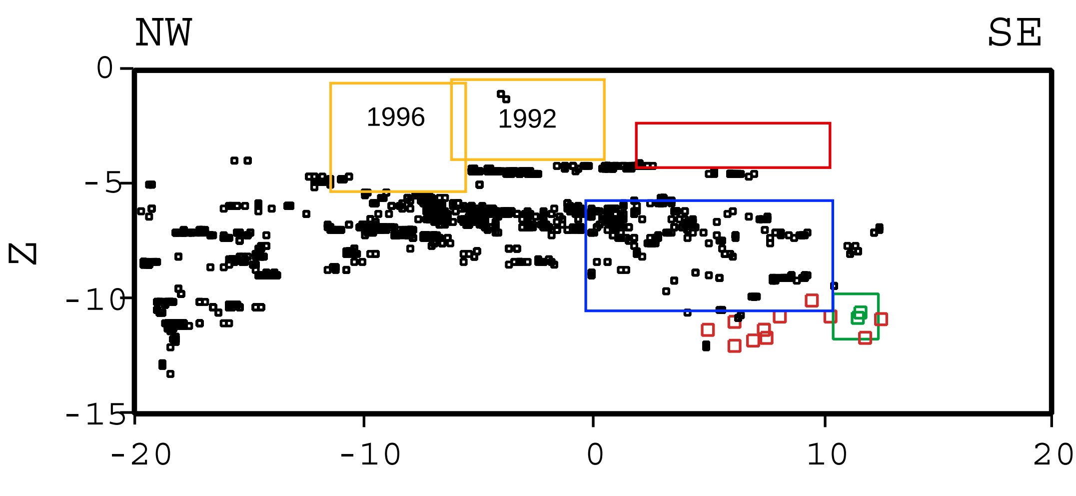

Figure 2. Comparison of August 17, 1998 foreshock and main shock locations (small and large green squares, respectively) with the estimated rupture area based on strain data (blue rectangle), the M > 2.6 aftershocks (red squares), the principal post-seismic slip event (red rectangle), and the relocated long-term seismicity of Rubin et al. (1999) (small black squares). Also shown are the 1992 and 1996 slow earthquake slip patches (orange rectangles).

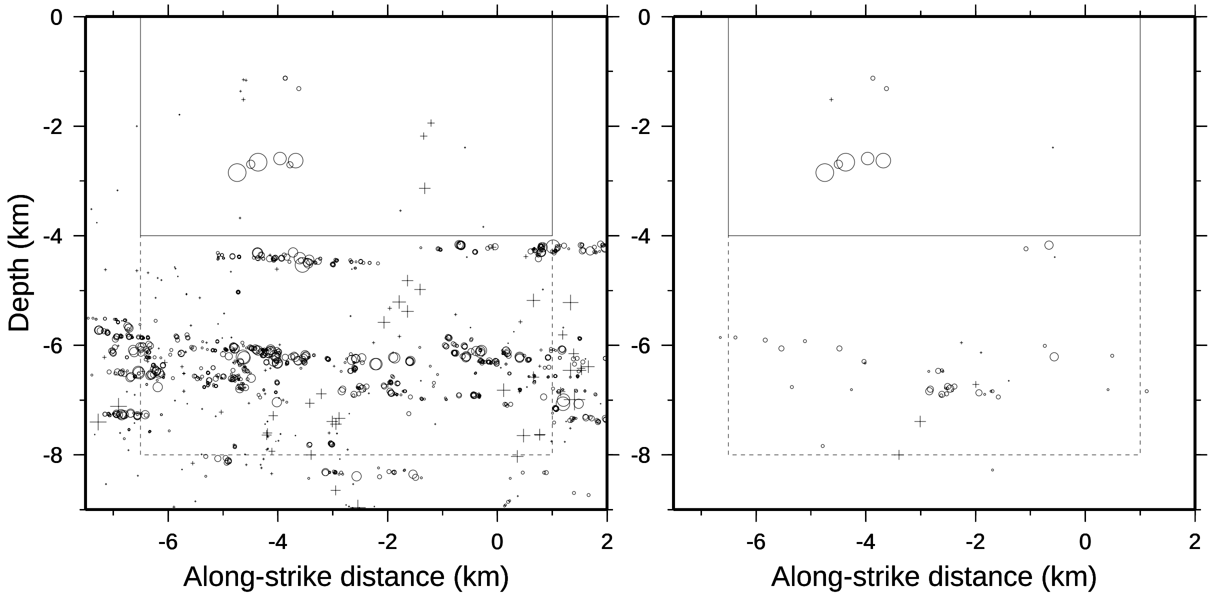

Figure 3. Geometry of the slow earthquake of 12/11/92, as determined by strainmeter data (Linde et al., 1996), in relation to the long-term structure of microsesmicity in the region, as determined from precise relative relocations (Rubin et al., 1999). View is a vertical cross-section looking NE. The slow earthquake extended at least as deep as 4 km (solid lines) and perhaps as deep as 8 km (dashed lines). Left, all the relocated (circles) and unrelocated (crosses) seismicity from 1984 through 1998. Symbols indicate approximate rupture size. Right, seismicity from 12/11/92 to 5/6/93. Note the strong concentration of seismicity at 4 km depth on the left that is absent following the slow earthquake. Until the onset of the slow earthquake, the seismicity rate in the band of seismicity at 4 km depth tracks very closely that in the band at 6 km depth. .

San Juan Bautista Array

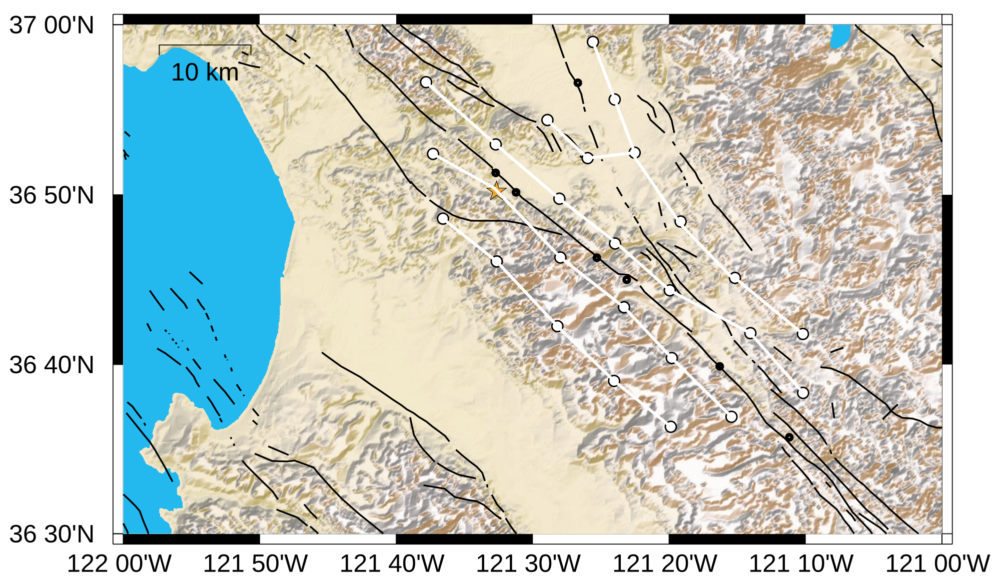

Figure 4. Proposed deployment plan for the San Juan Bautista region. The existing SJT BTSM site is indicated by the red star, with existing surface creepmeters along the fault trace as black circles. Approximate locations for the proposed new BTSM sites and the associated GPS and seismometer/strong motion sites are shown as white circles.