INTERSEISMIC BACKGROUND SEISMICITY OF THE SOUTHERN SAN ANDREAS FAULT, CALIFORNIA

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ABSTRACT

We analyze the spatial distribution of background seismicity located within 2 km of the surface trace of the San Andreas fault. The spatially scattered seismicity surrounds an approximately 0.4-km-wide aseismic zone that spans the whole length of the southern San Andreas fault. The maximum depth of seismicity is greater to the west and smaller to the east of this aseismic zone. We presume that this aseismic or locked region is the damage zone that surrounds the slip plane where major or great earthquakes rupture along the San Andreas fault. This lack of seismicity along the locked zone is possibly related to fault properties such as the strength of the fault, the local stress field, and the mechanics of major or great earthquakes. Thus the seismicity adjacent to the San Andreas appears to occur within the edges of major crustal blocks rather than occurring within the locked fault zone itself. We also compare the seismicity distribution of the San Andreas fault with the distribution of the foreshocks and aftershocks of the 1992 M_w7.3 Landers mainshock relative to the mapped surface rupture. The foreshocks occurred within a 0.5-km-wide zone. The mainshock and immediate aftershocks occurred within and adjacent to this 0.5-km zone. The aftershocks within this zone appear to decay more rapidly than events outside of it. Thus the Landers data suggest that the locked zone accommodates foreshocks, the mainshock, and some of the aftershocks but remains aseismic during most of the interseismic period.

INTRODUCTION

The San Andreas fault is the fastest moving fault in California and is responsible for many of the largest earthquakes. These earthquakes occur on average every 150 to 350 years and have the longest ruptures and largest slips (*Sieh et al.*, 1989). The cumulative offset on the San Andreas fault is much larger compared to other faults in southern California, exceeding 300 km, and thus its fault zone properties may differ from other faults in southern California (e.g. *Irwin*, 1990)

The San Andreas fault is characterized by a low level of background seismicity when compared with some other strike-slip faults in southern California such as the San Jacinto and Newport-Inglewood faults (*Hauksson*, 2000). It is often found that events occur close to, but not within the San Andreas fault zone. Some previous studies have suggested that there are no small earthquakes occurring within the southern San Andreas fault zone proper (*Jones*, 1988). The purpose of this study is to use more accurate earthquake locations to verify if any of the background seismicity is occurring within or just adjacent to the San Andreas fault. If the seismic signature of the fault zone differs from the adjacent blocks, it may contain important information about the constitutive properties of the San Andreas fault.

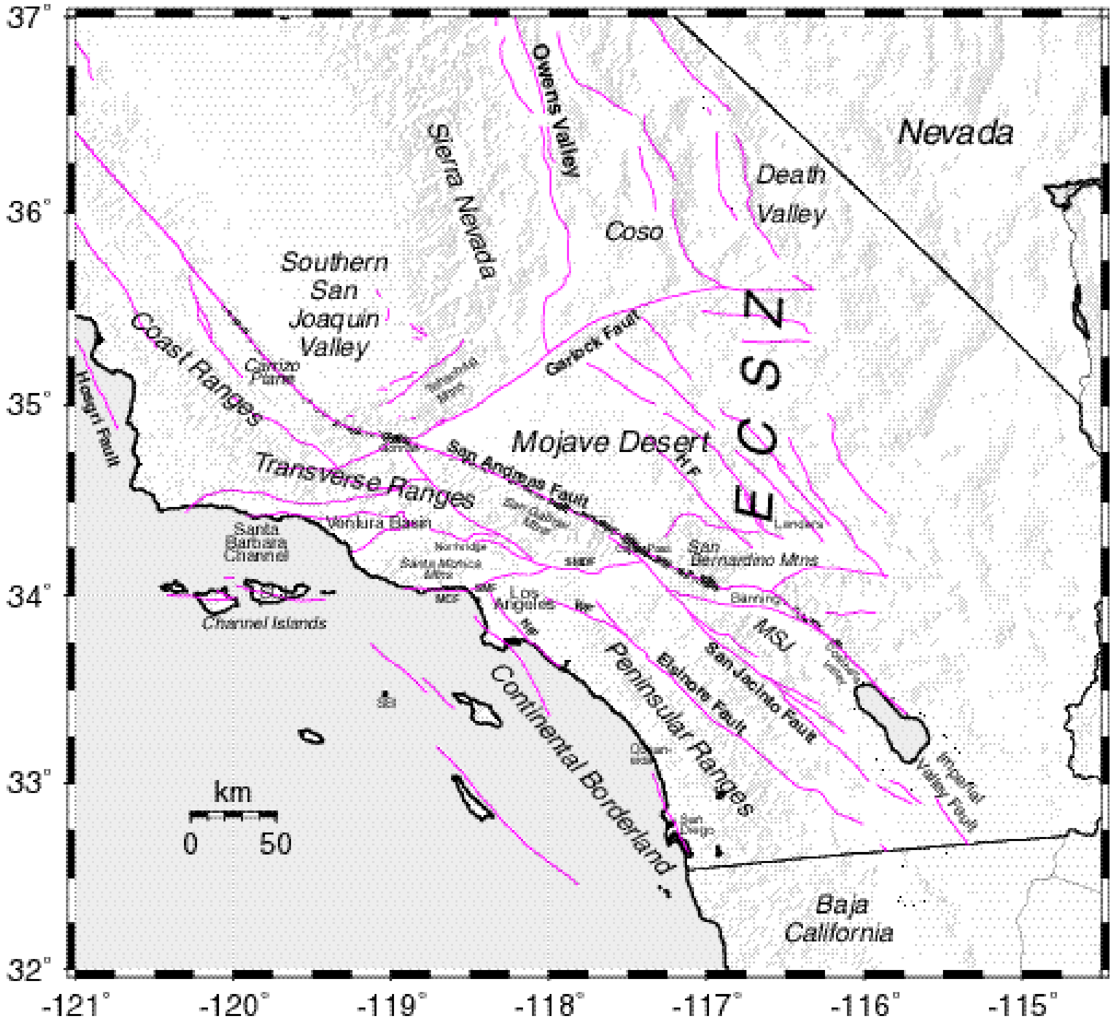

Figure 1. A map showing the location of the study area, including the San Andreas fault and other late Quaternary faults. The seismicity within 2 km of the southern San Andreas fault is also shown.

There are several lines of evidence suggesting that the San Andreas fault zone has different constitutive properties from the adjacent blocks. Most often it is inferred to be a zone of weakness. For instance, the observed high angle of the maximum horizontal stress to the San Andreas fault has been used to infer that the fault zone itself is weak (e.g. *Zoback et al.*, 1987). The velocity structure of the San Andreas fault is known on a scale of a few kilometers where the two LARSE seismic lines cross the San Andreas fault

(*Fuis et al.,* 2000). Both seismic lines suggest that there is a low velocity zone along the San Andreas fault trace.

We analyze the 1981 to 2000 background seismicity along the southern San Andreas fault. We determine the geometrical shape of this aseismic damage zone along the southern San Andreas fault by analyzing the seismicity within 2 km of the fault zone. We focus on this small distance to search for a narrow zone on the order of 100s of meters that may correspond to damage zones mapped in the field (*Chester et al.,* 1993).

We have used the new 3-D Vp and Vp/Vs velocity models of southern California with 15 km horizontal grid and approximately 4 km grid in depth, down to a depth of 22 km, (*Hauksson*, 2000) to relocate the seismicity. These hypocenters have horizontal and vertical errors that peak around 0.7 km. In this study we have included only events that have horizontal and vertical errors less than or equal to 1.0 km. Common biases in the hypocentral locations are constraining of focal depths to a layer boundary or a local minimum in a velocity model. Such biases are not observed along the San Andreas fault where the focal depths are well constrained. The absolute horizontal error should be less than 1 km, and relative errors are smaller still, (*Hauksson*, 2000).

THE SOUTHERN SAN ANDREAS FAULT

In this part of our study we focus on analyzing seismicity within 2 km distance of the San Andreas fault (Figure 1). The San Andreas fault can be divided into five segments in southern California, the Carrizo, Mojave, San Bernardino, Banning, and Indio segments, based on seismicity and geological mapping (*Sieh et al*., 1989; *Jones*, 1988). These segments have all generated large earthquakes in the past (*Sieh et al*., 1989). The two segments that most recently ruptured in the 1857 Fort Tejon earthquake, are the Carrizo and Mojave segments. We have chosen to exclude the Banning segment of the San Andreas fault because the active trace is not clearly expressed and it is unclear, if the fault dips to accommodate the localized curvature and the rapid change in strike. Also the relative slip rates of the Mill Creek and the Banning strands of the San Andreas are not well understood.

Figure 2 shows histograms of the number of earthquakes in 4 km distance profiles, centered on the San Andreas fault. Each profile includes the seismicity along the whole length of a segment. The rate of seismicity varies between segments, with the highest rate of seismicity corresponding to the San Bernardino segment. The lowest rate of seismicity is observed adjacent to the SAF trace along the Carrizo and Coachella Valley segments.

All four histograms show an aseismic zone centered on the mapped trace of the San Andreas fault. The aseismic zone is most prominent along the San Bernardino segment. This zone is least prominent along the Carrizo segment because of the low rate of seismicity. No other similar aseismic zones are observed away from the fault trace, out to distances of 2 km. The zone does not seem to change significantly in width along the whole length of the southern San Andreas.

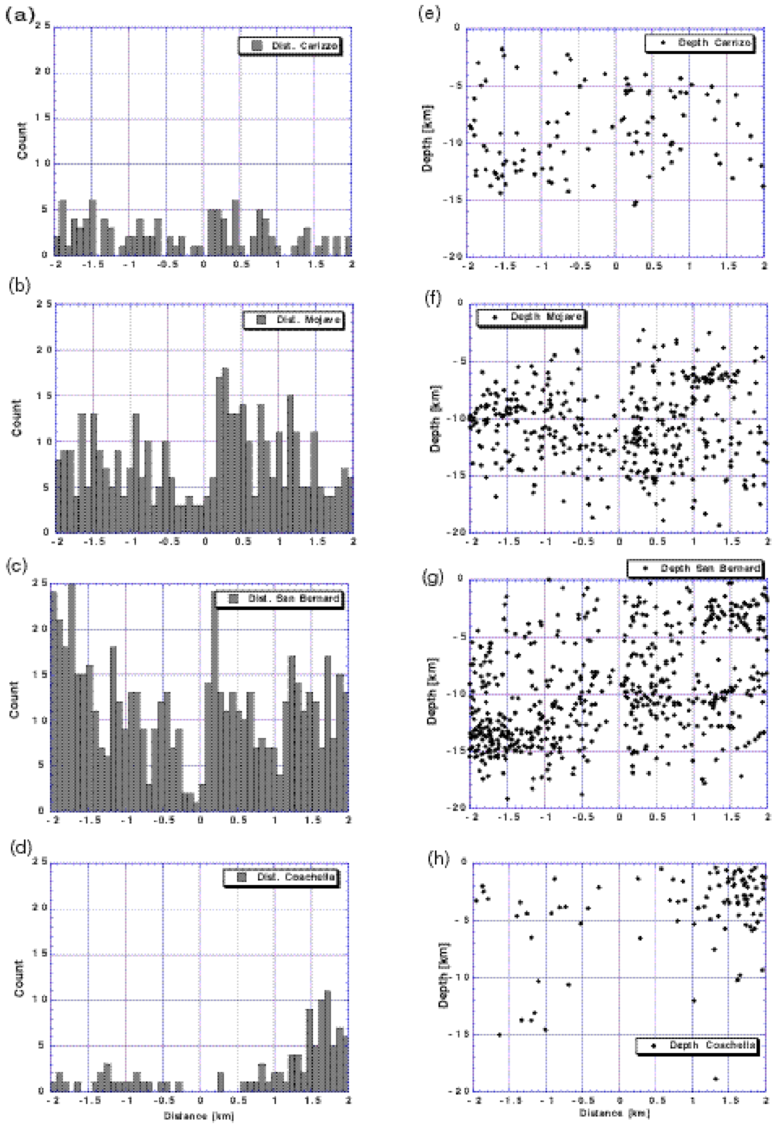

Figure 2. Histograms and cross sections of seismicity (1981 to 2000) along the four segments of the San Andreas fault; (a) Carrizo; (b) Mojave; (c) San Bernardino; and (d) Coachella Valley. Only events located within 2-km distance of the San Andreas fault are included.

The depth distribution of the events also varies from one segment to the next and emphasizes the presence of an aseismic zone. Along all of the segments, the overall spatial distribution has a different signature on the west side as compared to the east side. The San Bernardino segment shows clearly how the events are deeper on the west side than on the east side. On a more regional scale, this increase in the depth of seismicity to the west of the San Andreas fault is true in general for most of southern California (*Hauksson*, 2000). Similarly, the average Vp velocity structure is higher to the west of the fault, reflecting changes in geological rock properties.

THE 1992 LANDERS COMPARISON

The 28 June 1992 M_w7.3 Landers earthquake rupture began on the Johnson Valley fault. It was preceded by at least 25 immediate foreshocks that probably occurred on the mainshock rupture plane (*Hauksson, et al.*, 1993; *Dodge et al.*, 1995). Because background seismicity, foreshocks, and aftershocks, recorded during the last eight years, are available, this fault and the associated seismicity are ideal for comparison with the seismicity of the San Andreas fault.

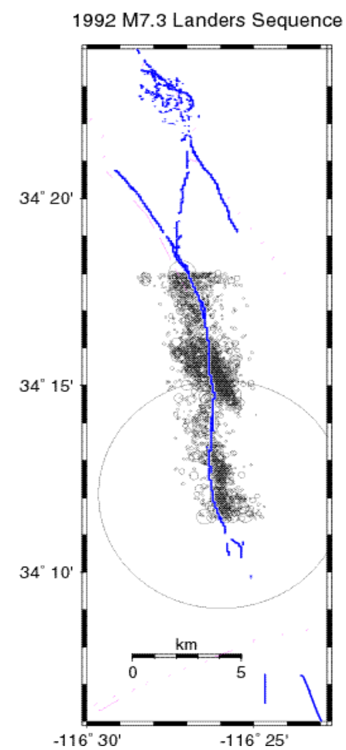

Figure 3. Map showing the Johnson Valley fault and the subset of Landers aftershocks used in this study.

We have analyzed seismicity located within 2 km distance of the Johnson Valley fault (Figure 3). The Landers rupture propagated to other faults but we use only data from the simpler Johnson Valley segment. The histograms of seismicity within 2 km distance of the Johnson Valley fault include pre-mainshock background activity, foreshocks, and three time periods of aftershocks (Figure 4). The low level of background seismicity does not show a clear lack of seismicity along the main fault strand. The foreshocks form a 0.5 km wide gaussian-like distribution centered at 0.2 km to the east of the fault trace.

This suggests that the absolute hypocenters are biased by a 0.2 km to the east of the Johnson Valley fault. During the two periods of early aftershocks (July 1992 and 1995) the peaks of the aftershock distributions coincide with the peak of the foreshock distribution. The late aftershocks (1998 to September 1999) show how the aftershocks within 0.2 km distance of the fault have decreased more than the aftershocks further away. The most recent aftershocks (October 1999 to June 2000) do not show as clear a signal because the 16 October 1999 Mw7.1 Hector Mine earthquake triggered enhanced aftershock activity along the central core of the Johnson Valley fault.

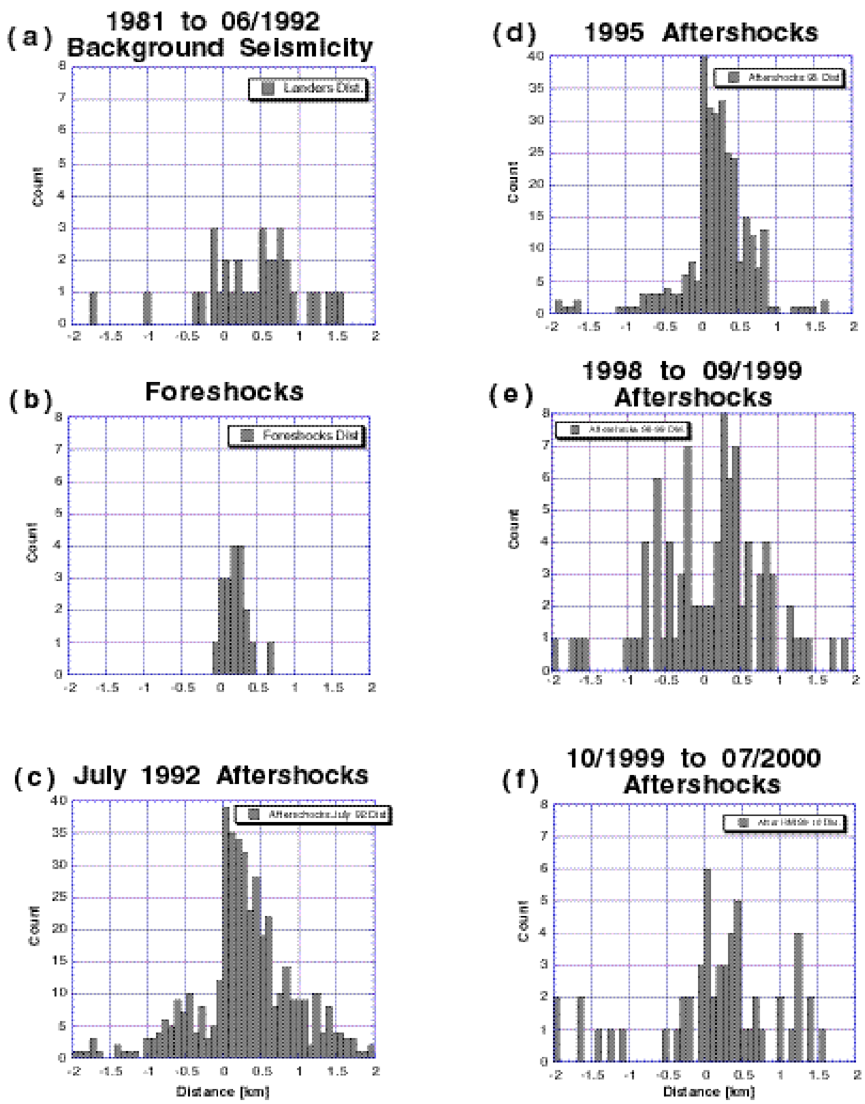

Figure 4. Histograms of the Landers background seismicity (1981 to June 1992), foreshocks (27^{th} and 28^{th} of June 1992), and aftershocks during four time periods; June 28 to July 31 1992; January to December 1995; and January 1998 to September, 1999; and October 1999 to July 2000.

The depth distribution of the Landers seismicity, located near the Johnson Valley fault, is shown in Figure 5. The constraints on the focal depths of these events are poor, particularly for the foreshocks. Following the Landers earthquake, additional seismic stations were installed, so the depth control for the aftershocks is better. The depth distributions of aftershocks show a concentration of aftershocks that coincide with the distribution of foreshocks. The aftershocks that occurred from 1998 to September 1999 show how the seismicity along the fault trace decreased more rapidly than the seismicity within the adjacent blocks.

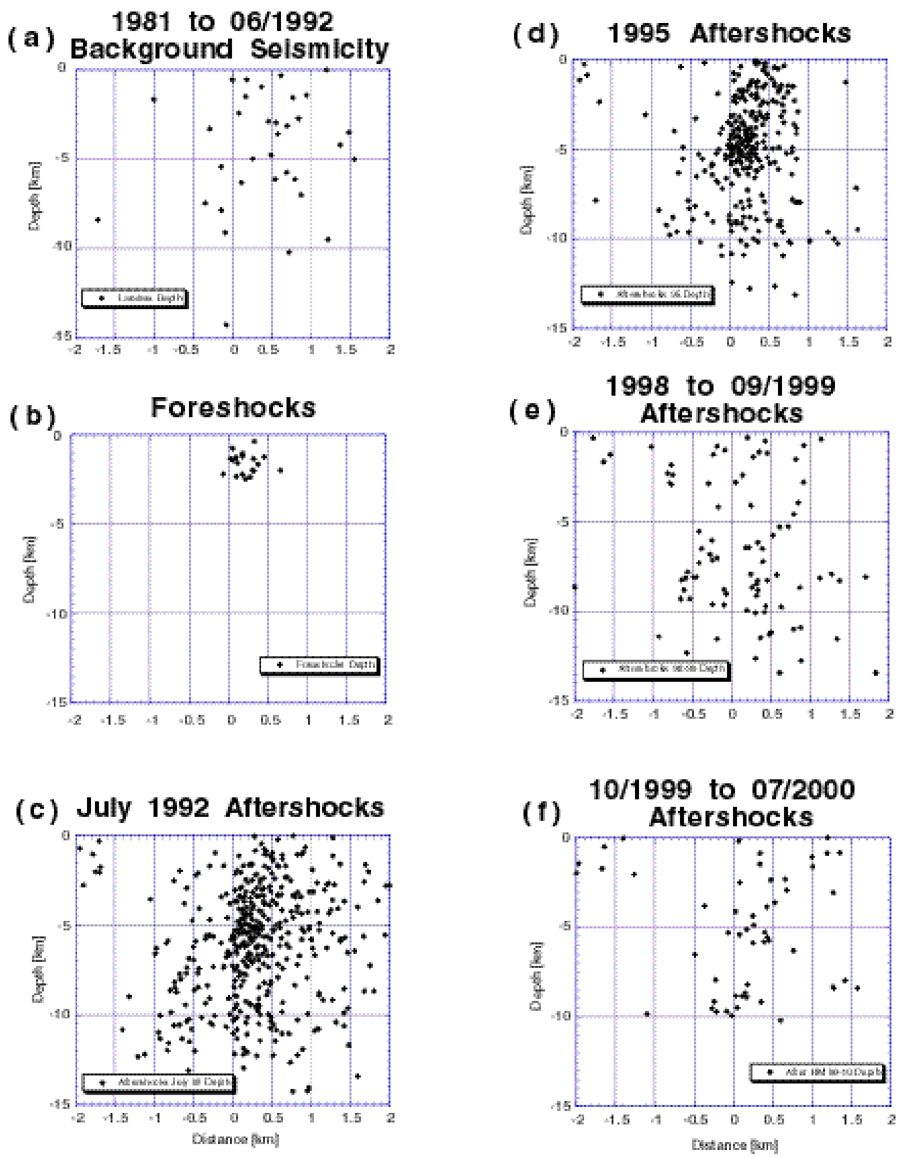

Figure 5. Depth cross sections across the Johnson Valley fault including same data as shown in Figure 4.

DISCUSSIONS AND CONCLUSIONS

The background seismicity pattern of small earthquakes in southern California has remained largely unexplained for 70 years. Although this study is focused on the San Andreas fault, it has implications for understanding the background seismicity in general. The background seismicity mostly occurs within blocks and along the edges of major blocks. In contrast major fault zones appear to remain mostly aseismic during the interseismic period.

The Landers earthquake sequence provides new insight into seismicity patterns along faults capable of generating major earthquakes. The long term background seismicity is very low, or absent along the main fault trace. Foreshocks, the mainshock, and aftershocks during the first few years occur along the main fault trace. After five to six years the aftershocks along the main fault trace have decayed away and only aftershocks located within the edges of the main blocks remain.

We interpret the approximately 0.4 km wide aseismic zone observed in this study as the damage zone around the fault core that contains the slip zone. In general the slip zone that is the rupture surface of an earthquake may be less than tens of centimeters wide (*Chester et al.*, 1993). However, because such a rupture surface will bend around as it encounters different stress states, and material heterogeneities, a damage zone is created over time. Fault zone trapped modes are a different way of getting at the velocity structure of the damage zone. For instance, *Li et al.* (1994) recorded anomalous waves on sensors placed in an array crossing the Johnson Valley fault. They inferred a 200 m wide fault zone of low velocity, are similar to the width of the damage zone found in this study.

The 0.4 km aseismic zone is too wide to fit the *Rice* (1992) model of a weak fault core. In the Rice's model, the weak zone and potential stress rotations are restricted to a thin fault zone of a width of less than 100 m, possibly less than 10 m. This would imply a smaller fault core within the 0.4 km damage zone, perhaps similar to that described by *Chester et al.*, (1993) for the San Gabriel and Punchbowl fault. The spatial resolution of the locations in this study is inadequate to resolve such a small feature.

The pattern of background seismicity reported in this study is different from seismicity patterns often reported along some of the creeping faults in northern California. For instance, *Waldhauser et al.* (1999) report high-resolution relative earthquake locations along the northern Hayward fault in northern California. They find that the fault zone width is less than 100 m and hypocenters occur within narrow lineations. These lineations may represent smearing of frictionally weak materials along the fault plane.

The pattern along the southern San Andreas fault however, compares well with the seismicity patterns inferred by *Zoback et al*. (1999) along the locked Peninsula segment of the San Andreas fault, located south of San Francisco. They found a similar seismic locked zone, about 1 km wide, and clusters of seismicity at different depths on either side. This difference in seismic behavior of creeping versus locked faults may be a result of their difference in relative strength. Such a strength difference is also suggested by the orientation of the maximum horizontal stress. In northern California the maximum stress direction is almost orthogonal to the strike of the fault (*Zoback et al*., 1987). In southern California the stresses are oriented at somewhat higher angles, or in the range of 50° to 80° (*Jones*, 1988, and *Hardebeck and Hauksson*, 1999).

One of many possible models is that the creeping faults only have a narrow and highly compliant fault zone, but not a well-developed wider damage zone. The background seismicity occurs where the two adjacent crustal blocks penetrate the fault zone and maintain frictional contact. In contrast the locked zones have a core fault zone and an outer damage zone. The damage zone is sufficiently wide and compliant to form a transition zone where the stress state changes. The background seismicity is concentrated at the outer edges of the damage zone and does not extend into the damage zone or the fault zone itself. When the core fault zone approaches failure, foreshocks and the mainshock, and early aftershocks occur within the damage zone and possibly within the core fault zone. In some cases triggered seismicity may occur along the damage zone, as illustrated by our observations along the Johnson Valley fault following the 1999 Hector Mine earthquake.

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Discussion:

Ze'ev Reches (Hebrew U.): Is the locked zone stronger/weaker than the areas on either side?

Egill Hauksson: I deliberately avoided using the terms strong or weak in my talk.You see the seismicity jumping back and forth across the fault/seismic gap, which might tell us something about the strength of the fault, but I'll leave it up to the members of the audience to decide.

Ze’ev Reches: It might be stronger in that it can sustain the stresses without sustaining any seismicity.

Egill Hauksson: Well, even if it were extremely strong it would control the seismicity in the adjacent rock. I don't think that is happening; I think that the adjacent rocks may be experiencing a different stress field, and that controls the seismicity.

Ross Stein (USGS, M.P.): You showed a remarkable trend in seismicity in Cucamunga, perpendicular to the San Andreas Fault, that showed strike-slip focal mechanisms. What do you make of that?

Egill Hauksson: It depends on the model, but you can model these earthquakes as being related to the San Andreas Fault.

Heidi Houston (UCLA): Do you really know where the San Andreas is at depth?

Egill Hauksson: I don't think that there's any doubt that it's the fastest-moving fault in California, and to first order in my mind, in most places, it is vertical.

Heidi Houston: The second comment is that your work reminded me of those cartoons of Allan Rubin, where the seismicity is divided into two blocks, one on either side of the fault. Don't you think this will confuse the issue by insisting that there's a half-kilometer wide zone where there's no seismicity?

Egill Hauksson: Allan Rubin was talking about the velocity structure of the San Andreas. These are first order observations, and so I don't think that they confuse the issue. If there were earthquakes in this zone, they would be mostly strike-slip and we don't see that.

Al Lindh (USGS, M.P.): In Mary Lou Zoback's work and in previous work on the peninsula, even though most of your data show thrust mechanisms, you see some small events (like 2's) that are clearly strike-slip and vertical, parallel to the San Andreas. Do you see anything like that in Southern California, like in the Mojave?

Egill Hauksson: I don't see anything like that in the Mojave. But I think that those are the kinds of earthquakes that we should be looking for, because they have different focal mechanisms and that may be able to tell us something about the adjacent rocks.

Amos Nur (Stanford U.): You showed seismicity which occurred over the last 18 years. Do you think that this represents long-term seismicity? The San Andreas doesn't even show up here. What will the pattern look like in the next 50 years?

Egill Hauksson: I think that 50 years from now it would look similar to this, but maybe 500 years from now you would get a pattern around the San Andreas fault. 500 years from now, it would look completely black. This is just a seismicity map, and doesn't say anything about recurrence times, etc.