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Healing of the shallow fault zone from 1994-1998 after the 1992 *M*7.5 Landers, California, earthquake

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Abstract. We conducted seismic surveys at the Johnson Valley fault in 1994, 1996, and 1998. We found that the shear velocity of the fault zone rock increased by ~1.2% between 1994 and 1996, and increased further by ~0.7% between 1996 and 1998. This trend indicates the Landers rupture zone has been healing by strengthening after the mainshock, most likely due to the closure of cracks that opened during the 1992 earthquake. The observed fault-zone strength recovery is consistent with a decrease of ~0.03 in the apparent crack density within the fault zone. The ratio of decrease in travel time for P to S waves changed from 0.75 in the earlier two years to 0.65 in the later two years between 1994 and 1998, suggesting that cracks near the fault zone are partially fluid-filled and have became more fluid saturated with time.

Introduction

Observations and numerical modeling of fault zone trapped waves generated by aftershocks and near-surface explosions have allowed us to delineate the fine internal structure of the Landers rupture zone [*Li et al.*, 1999; 2000]. The rupture zone is marked by a low velocity and low Q waveguide 250 m wide at the surface, tapering to 100-150 m at 10 km depth. Shear velocities of the rupture zone are reduced by 40-50% from those of the surrounding rock. Within the rupture zone, the shear-velocity increases from 1.0 km/s to 2.5 km/s and Q increases from 20 to 60 with depth. From the view point of fracture mechanics, the distinct low-velocity waveguide on faults may be a remnant of the process zone, which is inelastic deformation around the propagating crack tip during rupture.

The strength of the fault zone may vary over the earthquake cycle [*Vidale et al.*, 1994; *Marone et al.*, 1995]. Inferred healing is consistent with state- and rate-dependent healing models [*Dieterich*, 1978]. Rupture models that involve variations in fault-zone fluid pressure over the earthquake cycle have been proposed [*Sibson*, 1977; *Blanpied et al.*, 1992]. Knowledge of spatial and temporal variations in fault structure may help resolve these variations and predict the behavior of future earthquakes.

Data and Results

Our repeated seismic surveys using explosions at the Landers rupture zone in 1994 and 1996 have revealed that the waveguide along the Johnson Valley fault which was weakened by the dynamic rupture in the Landers earthquake of 1992 has been regaining strength with time [*Li et al.*, 1998]. This trend is most likely due to the closure of cracks that opened during the Landers mainshock. The closure of cracks increases the stiffness and frictional strength of the fault zone.

Our continued measurements of the Landers rupture zone in 1998 allow us to identify and interpret temporal and spatial variations of the fault-zone properties. Explosions were detonated in 35-m-deep shot holes drilled at the same sites SP3, SP4, and SP5 within the rupture zone as in 1994 and 1996 experiments (Figure 1). Each explosion used 250-500 kg of chemical emulsions. Signals generated by explosions were recorded at two 3-km-long linear seismic arrays perpendicular to the rupture zone (Line 1 and Line 3 in Fig. 1). Line 1 had 36 stations and Line 3 had 21 stations, using Mark product L22 sensors with REFTEK seismometers from PASSCAL Instrument Center. All stations were at the same locations in repeated experiments. Line 1 and Line 3 were located 9 km north and 4 km south of the Landers mainshock epicenter. Line 1 is centered at the region that experienced the 3 m maximum amount of slip on the Johnson Valley fault during the Landers earthquake. Slip was smaller near Line 3.

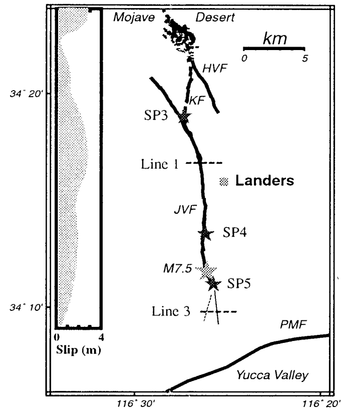

Figure 1. Map of the study region showing locations of seismic arrays at Lines 1 and 3 across the rupture zone of the 1992 *M*7.5 Landers, California, earthquake. Shots SP3, SP4, and SP5 were detonated within the rupture zone. Only the southern half of the Landers rupture lies in the map, and the dextral surface-fault slip profile (*Sieh et al.*, 1993) is shown in the inset. JVF, Johnson Valley fault; KF, Kickapoo fault; HVF, Homestead Valley fault; and PMF, Pinto Mountain fault.

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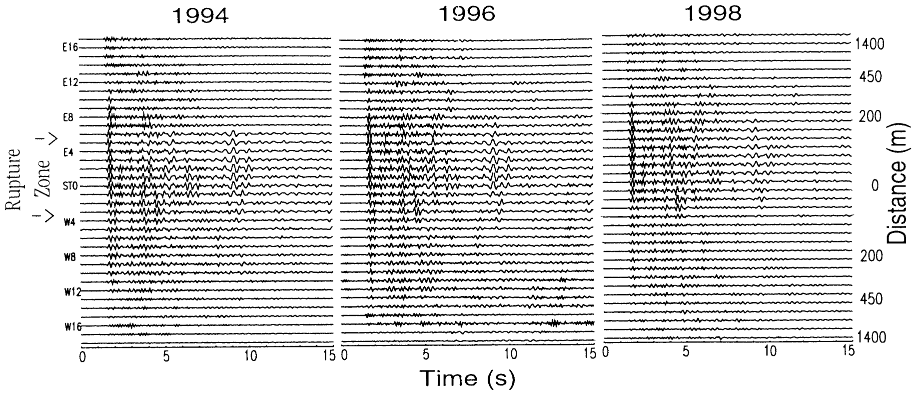

Figure 2. Vertical-component seismograms in the cross-fault profile at Line 1 for shot SP4 detonated in the Landers fault zone in 1994, 1996, and 1998. We recorded similar waveforms for *P* (arriving at ~1.7 s), *S* (at ~3.3 s), and fault-zone trapped waves following *S* waves in repeated experiments. Trapped waves were prominent at stations located within the low-velocity rupture zone (~250 m wide). Station spacings are uneven. Seismograms are low-pass filtered at 8 Hz and plotted with a fixed-amplitude scale for all traces.

Figure 2 shows seismograms in cross-fault profiles on Line 1 for shot SP4 detonated in 1994, 1996, and 1998. We recorded the similar wave forms of *P*, *S*, and trapped waves in repeated experiments, but with a time advance of tens of milliseconds for the 1996 recordings and further time advance in the 1998 recordings. In order to measure the advances in arrival time of these waves accurately, we extracted *P*, *S* and trapped waves from 3 time windows and cross-correlated each pair of recordings for the same shot and same seismometer to obtain time differences between the 1994 and 1996 recordings, and between the 1996 and 1998 recordings. Windows 1 and 2 have *P* and *S* waves, respectively. Window 3 has the first fault-zone trapped waves. All phases of the seismic waves traveled fastest in 1998 and faster in 1996 than in 1994.

One example is shown in Figure 3. The peaks of the cross-correlation are almost one, indicating waveform similarity between repeated experiments. The travel times of these waves decreased several tens of milliseconds from 1994 to 1998. These changes are an order of magnitude larger than the uncertainty in the origin time of the explosion, which is less than a few milliseconds. The advances in arrival time increased progressively with longer travel times for *P*, *S*, and trapped waves.

If the changes in velocity were uniform through the crust that was sampled by these waves, the decrease in travel times would be straightforward to interpret. For example, in Fig. 3a, the *P* wave arrived 26 ms earlier in window 1, with a travel time of 1.7 s, so the *P* wave velocity increased by ~1.5% between 1994 and 1996. Similarly, the *S* wave arrived 35 ms earlier, with a travel time of 3.3 s, so the *S* wave velocity increased by ~1.1%. The trapped waves in window 3 with longer travel times of 4.5 s had a larger time advance than *P* and *S* waves of 50 ms, again showing ~1.1% increase in velocity. Comparing the 1996 and 1998 records, the *P* wave arrived 15 ms earlier in window 1, the *S* wave arrived 22 ms earlier in window 2, and trapped waves arrived 32 ms earlier in window 3, so the velocity of the *P* wave further increased by ~0.9% and the velocity of *S* and trapped waves increased further by ~0.66%.

Figure 4 shows the decrease in travel time of *P*, *S* waves and trapped waves at all stations on Line 1 and Line 3 for SP4 and SP5 between 1994 and 1996, and between 1996 and 1998. The data for SP3 were not used because SP3 was a dead shot in the 1996 experiment. Larger changes in arrival times were observed at stations located close to the fault trace, with a travel time decrease of ~1.6% for *P* waves and ~1.2% for *S* and trapped waves between 1994 and 1996, which was further reduced by ~0.9% for *P* waves and ~0.7% for *S* and trapped waves between 1996 and 1998. In contrast, the travel times of *S* waves to stations in surrounding rock sides decreased by 0.4% between 1994 and 1996, and by <0.2% more between 1996 and 1998. These observations indicate that the Landers rupture zone has been healing by strengthening with time since the 1992 earthquake, and that the healing rate is decreasing with time. Based on the width of the zone exhibiting larger arrival time decreases, we estimate that the Landers rupture zone in the top a few kilometers is ~300 m in agreement with our guided wave studies [*Li et al.*, 1999]. The ratio of decrease in travel time for *P* to *S* waves (Δtp/Δts) for all repeated shot-receiver pairs are also shown in Figure 4. The mean Δtp/Δts was 0.75 between 1994 and 1996, but decreased to 0.65 between 1996 and 1998.

We use equations for the elastic moduli of a medium with isotropically-oriented penny-shaped cracks [*Garbin and Knopoff*, 1975] to model the observed healing of the fault zone. In reality, cracks may not be isotropically oriented because there may be some alignment according to the stress regime. However, the coherence is not simple to predict and may change with time as has been claimed at the Nojima fault in Japan [*Tadokoro et al.*, 1999]. We have considered the possibility of aligned cracks, but closure of isotropically oriented cracks is more consistent with the observed Δtp/Δts. For either wet or dry aligned cracks, Δtp is much smaller than Δts, so closure of aligned cracks doesn't affect *P* waves nearly as much as it affects *S* waves. In our model of isotropically-oriented cracks, a change in the density of dry cracks in a Poisson solid is predicted to cause Δtp/Δts ~1.22. Water-saturated cracks, on the other hand, cause Δtp/Δts only of ~0.27. However, in our study area, the rock has an anomalous Poisson's ratio such that the *P* wave velocity is about twice the *S* wave velocity. In this case, Δtp/Δts is predicted to be 1.64 for dry cracks and

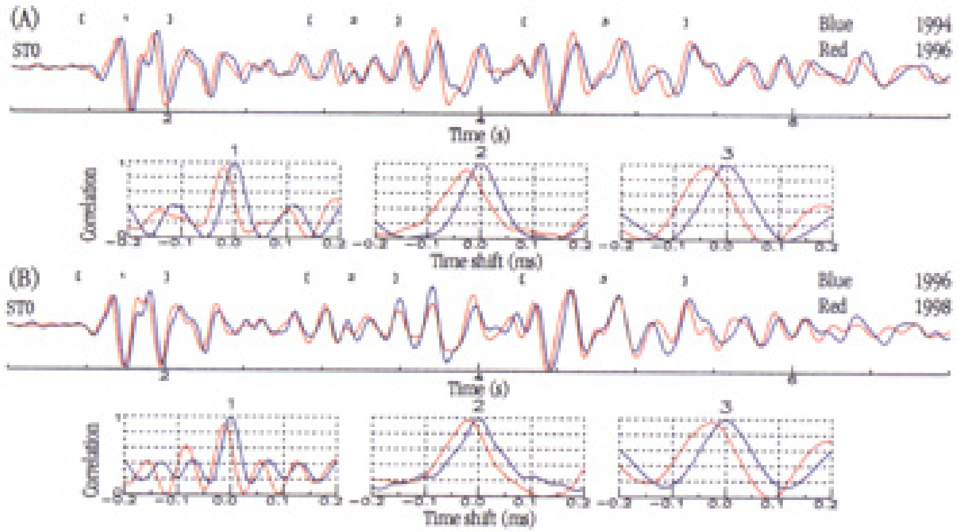

Figure 3. (A) top: Vertical-component seismograms recorded at station ST0 of Line 1 for shot SP4 in 1994 and in 1996. Station ST0 was located within the Landers rupture zone. Bottom: Auto-correlations (blue lines) of seismograms recorded in 1994 and cross-correlations (red lines) of recordings in 1994 and 1996 at the same station for 3 time windows [1] to [3] including *P*, *S*, and trapped waves, respectively. The peak of the autocorrelation curve is at zero lag time in each window. The negative time shift indicates time advance. The cross-correlations in windows 1 to 3 reveal time advances of 26, 35, and 50 ms for *P*, *S*, and trapped waves. (B) Same as (A) for 1996 and 1998. Time advances of 15, 22, and 32 ms for *P*, S, and trapped waves are measured. Traveltime advances between 1996 and 1998 recordings were smaller than those between 1994 and 1996 recordings.

0.17 for wet cracks. So the $\Delta tp/\Delta ts$ ratios observed between 1994 and 1998 indicate that cracks within and near the rupture zone were partially water filled and became more wet with time after the Landers earthquake.

The increase in *P* and *S* wave velocities with time is most likely due to the closure of cracks as the crust heals after the earthquake. This process may be thought of as reductive dilatancy. Estimates of the change in velocity due to the change in crack density may be calculated with equations in which the elastic constants of fractured rock are functions of the crack density [*O'Connell and Budiansky*, 1974]. We assumed randomly-oriented cracks. We computed the change in apparent crack density from measured change in seismic velocity. The apparent crack density is defined by $e = N\langle a^3\rangle/V$, where a is the radius of the penny-shaped crack and N is the number of cracks in a volume V. We assumed cracks to be partially-water filled, and estimated that Poisson's ratio is 0.34. In our calculation, average Vp = 3.0 km/s and Vs = 1.5 km/s for the fault-zone rock at the shallow depth. These values are consistent with our velocity model for the shallow Landers rupture zone [*Li et al.*, 1999]. Our calculations indicate that the apparent crack density within the rupture zone decreased by 1.8% between 1994 and 1996, and decreased by an additional 1.1% between 1996 and 1998.

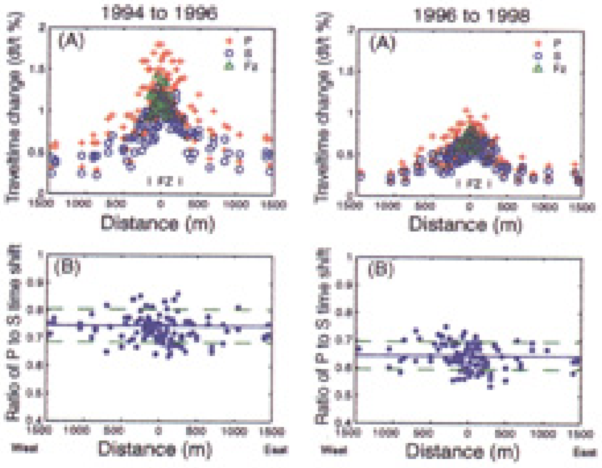

Figure 4. (A) Travel time decreases in percent for *P* , *S* and fault-zone trapped waves determined from cross-correlations of seismograms recorded at Lines 1 and 3 for shots SP4 and SP5 in repeated experiments. The greater changes in travel time appeared at stations within the Landers rupture zone. Travel times decreased more between 1994 and 1996 than between 1996 and 1998. (B) Ratio of travel time decrease for *P* to *S* waves. The mean ratio (solid line) was 0.75 with a standard deviation (dashed lines) of 0.06 between 1994 and 1996, but decreased to 0.65 with a standard deviation of 0.05 between 1996 and 1998.

Discussion

We have observed an ~1.9% increase in shear velocity within the shallow Landers rupture zone to a depth of ~ 2km from 2 to 6 years after the Landers earthquake of 1992. This temporal change in seismic velocity resulted from an ~3% decrease in the apparent crack density, which caused ~4% increase in shear rigidity of the fault-zone rock, indicating that the Landers rupture zone has been healing since the 1992 earthquake. However, the healing rate is not constant but diminishes with time. It means that a fault may regain strength rapidly in the early stage of the interseismic period, but may take a long time to fully recover the strength for the next earthquake on it.

Faults in the eastern Mojave shear zone are characterized by long earthquake cycle on them [*Sauber et al.*, 1994].

The recurrence of faulting on the Johnson Valley fault is estimated to exceed 1000 years [*Sieh et al.*, 1993]. Experimental studies [*Kanamori and Allen*, 1986; *Houston*, 1990] indicate that a longer interval since the previous episode of faulting correlates with higher stress drop in the subsequent rupture. The Landers fault zone in 1992 earthquake showed a high stress drop of ~200 bars, consistent with long interval of healing.

Although we focus on time-dependent healing of the Landers rupture zone in terms of the crack density change to explain the observed seismic velocity, it may be combined with other effects such as the time-dependent frictional strengthening [*Marone*, 1998], fluid variations or changes in the state of stress [*Sleep and Blanpied*, 1994; *Palmer et al.*, 1995; *Dodge and Beroza*, 1997] as well as the normal compaction of the rupture zone [*Massonnet et al.*, 1996]. However, the 'crack dilatancy' mechanisms associated with the earthquake we discussed above are likely to operate for fault healing with time even if other processes are active too. Because our observed ratio of P to S traveltime reduction is lower than the predicted ratio for dry cracks, some fluid is likely to be present in cracks after an earthquake. We also found that the cracks became more wet with the time. This may be due to the feedback of fluids into the fault zone in the interseismic period or due to the closure of cracks.

The reduction in apparent crack density might be detectable in geodetic measurements. As rocks heal, there can be either more of the right-lateral shear deformation from the regional stress field that dominates the coseismic displacements, or fault-normal compression from the reduction in volume. For the 1989 Loma Prieta, California, earthquake, there is evidence of several cm/yr of fault-normal contraction in the years following the event [*Savage et al.*, 1994]. Fault-normal contraction for Landers rupture zone with a time scale of several years has also been reported [*Massonnet et al.*, 1996]. At Landers, synthetic aperture radar images revealed uplift and depression with a one year time scale that is consistent with re-equilibration of pore fluids due to mainshock-induced stresses [*Peltzer et al.*, 1998].

In our study, we conclude that some cracks which had opened during the mainshock closed soon thereafter. Closure of cracks increase the frictional strength of the fault zone, as well as its stiffness. This is consistent with our tentative interpretation of the strong low-velocity Landers fault-zone waveguide as being at least partially created during the mainshock and also helps explain observations of increasing stress drop with increasing recurrence intervals.

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