Detect Water-Saturation Degrees within the Fault Zone during Co-Seismic Damage and Post-Seismic Heal

Yong-Gang Li (University of Southern California, ygli@usc.edu)

Abstract

Our repeated experiments to record seismic waves from explosions and earthquakes at dense linear arrays deployed across rupture zones of the 1992 M7.4 Landers, 1999 M7.2 Hector Mine and 2004 M6 Parkfield earthquakes revealed fault co-seismic damage and post-seismic heal progression. These observations suggest that a fault damaged in the earthquake may regain strength rapidly in the early stage of the interseismic period, but take a long time to fully recover the strength for the next earthquake on it. We consider that the "crack dilatancy" mechanisms associated with the earthquake are likely to operate for fault damage and healing. Co-seismic deformation might lead to crack opening either by elevated pore fluid pressure or stress drop. After the earthquake, crack healing, fluid diffusion and post-seismic deformations cause the cracks to close again with a logarithmic recovery rate. In this study, we measured the ratio of traveltime decreases for P to S waves recorded for the same shot-receiver pairs in repeated experiments to detect variations in water-saturation degree of cracks within the rupture zone during co-seismic damage and post-seismic heal. According to equations for the elastic moduli of the medium with penny-shaped cracks, the ratio of Δtp/Δts is ~1.22 for dry cracks, and ~0.27 for water-saturated cracks in a Poisson solid. In our study area where the rock has an anomalous Poisson's ratio of 0.33, Δtp/Δts is 1.64 for dry cracks and 0.17 for water-saturated cracks. At Parkfield, we measured the Δtp/Δts to be 0.57 within the SAF rupture zone and ~0.65 in the surrounding rocks between two shots detonated before and after the 2004 earthquake, indicating that cracks within the SAF are wetter than those out of the zone. Water may be coming up from depth along with the highly fractured fault-zone acting as a fluid conduit. The mean value of Δtp/Δts ratio (~0.72) bewen 2000 and 2001 observed at the Hector Mine rupture zone indicates that cracks within the fault zone were partially water filled after the 1999 earthquake. The Δtp/Δts ratio within the Landers rupture zone decreased from 0.75 between 2 and 4 years to 0.65 between 4 and 6 years after the 1992 M7.4 earthquake and further decreased to 0.55 until 2001, suggesting that cracks within fault damage zone became apparently more fluid saturated with time after the mainshock. These observations suggest that monitoring the temporal variations in Δtp/Δts ratio within the fault zone may play a role of precursor of pending earthquake on it.

Co-Seismic Damage of the SAF in 2004 Parkfield M6 Earthquake

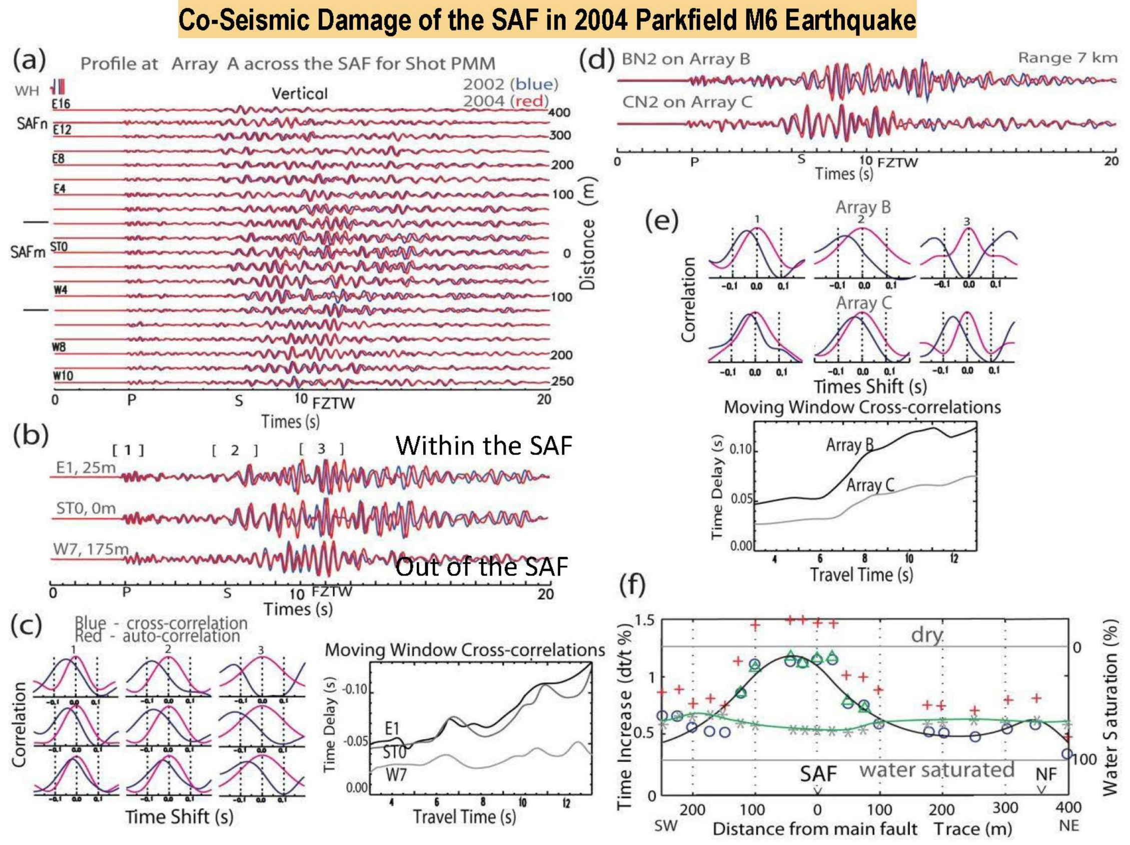

Fig.2 (a) Seismograms recorded at array A for repeated shot PMM in 2002 and 2004, show similar waveforms but travelling slower after the 2004 M6 Parkfield earthquake. **(b) S**eismograms at stations E1 and ST0 within and W7 out of fault zone. **(c)** cross-correlations and moving-window cross-correlations of seismograms in (b), show the traveltime delay after the M6 quake. **(d)** and **(e)** Sat array B and array C. **(f)** Traveltime increases of P (red), S (blue), and FZTWs (green) at array A for repeated shot PMM, Ratio of traveltime changes for P waves to S waves (green stars with a curve) Δtp/Δts is 0.57 within the SAF rupture zone and ~0.65 in the surrounding rocks between two shots before and after the M6 earthquake, indicating that the fault rocks are partially water saturated, and wetter than surrounding rocks. These observations suggest that co-seismic "crack dilatancy" mechanisms might lead to crack opening and increase the vacancy within the cracks which might be water saturated before the M6 earthquake occurred.

Formula used in this study

Garbin and Knopoff (1975a, b) analyzed a random distribution of penny-shaped parallel cracks in the rock and inserted the crack density ε defined by O'Connell and Budiansky (1974) into their formulas to obtain velocities of body-waves in dry cracks

$$V_p = V_{p0}\Big/\sqrt{1+\frac{8}{3}\varepsilon\left(\frac{8\mu s^2c^2}{3\lambda+4\mu}+\left[\frac{(\lambda+2\mu c^2)^2}{2\mu(\lambda+\mu)}\right]\right)}, \qquad V_s = V_{s0}\Big/\sqrt{1+\frac{16(\lambda+2\mu)}{3}\varepsilon\left(\frac{c^2\sin^2\varphi}{3\lambda+4\mu}+\frac{(1-2c^2)^2\cos^2\varphi}{3\lambda+4\mu}+\left[\frac{s^2c^2\cos^2\varphi}{2(\lambda+\mu)}\right]\right)}$$

where $V_{p0}=\sqrt{\frac{\lambda+2\mu}{\rho}}$ and $V_{s0}=\sqrt{\frac{\mu}{\rho}}$ are P- and S-wave velocities in uncracked isotropic rock, λ and μ are Lame constants for uncracked rock, $s=\sin\theta$ and $c=\cos\theta$, θ is the incident angle with respect to the normal of the crack plane, and φ is the angle between the polarization of the S-wave and the plane containing the incident ray. For the horizontal crack plane, $\varphi=0^{o}$ corresponding to SV-wave and $\varphi=90^{o}$ corresponding to SH-wave which polarization parallel to the crack plane. $\varepsilon=Na^3$ is the crack density where N is the number of cracks with radius a per unit volume. For water saturated cracks, the terms in brackets [ ] in equation are omitted.

We have considered the possibility of aligned cracks, but closure of isotropically oriented cracks is more consistent with the observed $\Delta t_p/\Delta t_s$. (Li, 1988; Li and Vidale, 2001; Li et al., 2003, 2006). According to the above equations and assuming for the Poisson solid, i.e. $\lambda=\mu$, the simplified equations to compute velocities of body-waves in the rock with material density ρ, and containing dry cracks and fully water-saturated cracks, are, respectively, written as

$$\frac{1}{V_P}=\left\{\frac{\rho}{3\mu}[1+2.49\varepsilon]\right\}^{1/2},\quad \frac{1}{V_S}=\left\{\frac{\rho}{\mu}[1+1.18\varepsilon]\right\}^{1/2} \qquad\qquad \frac{1}{V_P}=\left\{\frac{\rho}{3\mu}[1+0.406\varepsilon]\right\}^{1/2},\quad \frac{1}{V_S}=\left\{\frac{\rho}{\mu}[1+0.914\varepsilon]\right\}^{1/2}$$

Thus, the ratio of traveltime changes for P and S waves, $\Delta t_p/\Delta t_s$, in a Poisson solid containing dry cracks and completely water-saturated cracks are, respectively, given by

$$\frac{\Delta t_p}{\Delta t_s}=\left(\frac{2.490}{1.180}\right)\left(\frac{\mu}{\lambda+2\mu}\right)^{1/2}=1.22 \qquad\qquad \frac{\Delta t_p}{\Delta t_s}=\left(\frac{0.406}{0.914}\right)\left(\frac{\mu}{\lambda+2\mu}\right)^{1/2}=0.27$$

More precisely, in our study area, the rock has an anomalous Poisson's ratio (0.33) such that the P-wave velocity is about twice the S-wave velocity. In this case, $\Delta tp/\Delta ts$ has two end-member values: 1.64 for completely dry cracks and 0.17 for fully water-saturated (wet) cracks in rock.

Conclusion

1. In rapid response to the 1992 M7.4 Landers, 1999 M7.1 Hector Mine and 2004 M6 Parkfield earthquakes in California, we deployed linear seismic arrays across and along the surface ruptures, and recorded FZTWs generated by aftershocks and explosions. Observations and 3-D finite-difference simulations of these FZTWs in terms of a multi-layer LVWG, we extracted 100-250-m-wide fault damage zones of these strong quakes, which extend to depths of 6-8 km and within which velocities are reduced by 25-50% from wall-rock velocities. A fault-zone LVWG has a capability to remarkably amplify the strong ground motion that should be considered in sake for earthquake hazard prediction.
2. Our repeated experiments at rupture zones of these major earthquakes in California reveal the co-seismic damage and post-seismic healing processes. We suggest that co-seismic "crack dilatancy" mechanisms might lead to crack opening with vacancy increase within the cracks, and then post-seismic crack closure with water filling and/or vacancy decrease.
3. We measured the variations in Δtp/Δts ratio within the Landers rupture zone, which decreased with years after the 1992 M7.4 mainshock, suggesting that cracks within fault damage zone became apparently more fluid saturated with time after the mainshock probably either due to gradually closing of cracks which were co-seismically opened or post-seismically water filling into fault zone. These observations suggest that monitoring the temporal variations in Δtp/Δts ratio may play a role of precursor of pending earthquake on the active fault in study.

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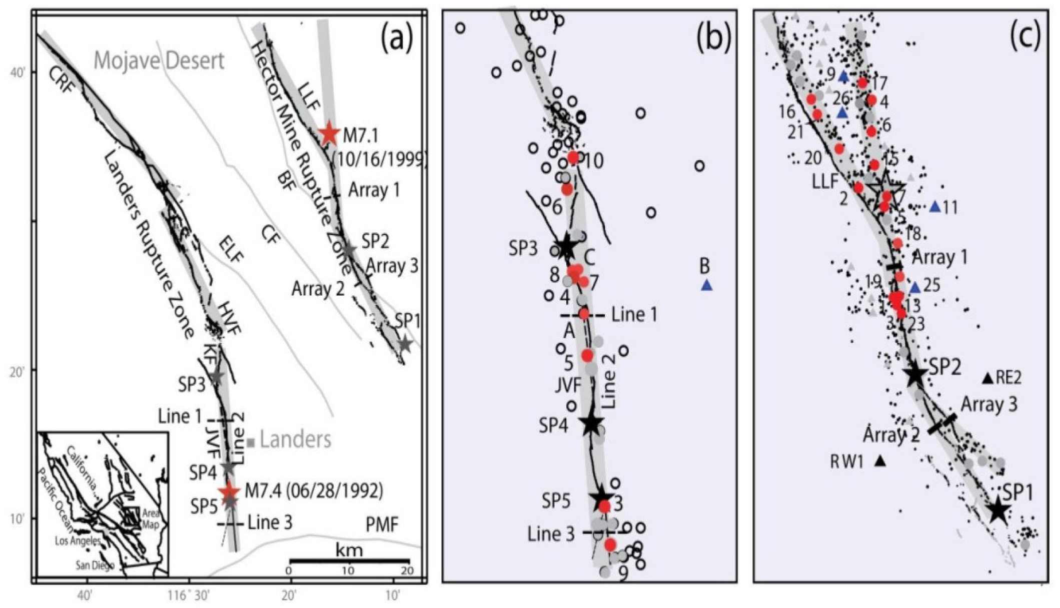


Fig.1 Left: (a) Maps show locations of seismic arrays with line number deployed at rupture zones (grey belts) of the Landers and Hector Mine (HM earthquakes in S. California, explosions (with SP number) detonated within the ruptures. **(b)** Map of Landers region shows locations of arrays across and along the Jonson Valley Fault (JVF), shots in the repeated surveys between 1994 and 2001, and aftershocks (circles) recorded during experiments. Red circles with labels denote aftershocks showing fault-zone trapped-waves (FZTWs) with long durations and the post-S time to P-to-S arrival time (PSSP) ratio >1.2. **(c)** As the same in (b) but for repeated experiments Hector Mine region in 2000 and 2001.

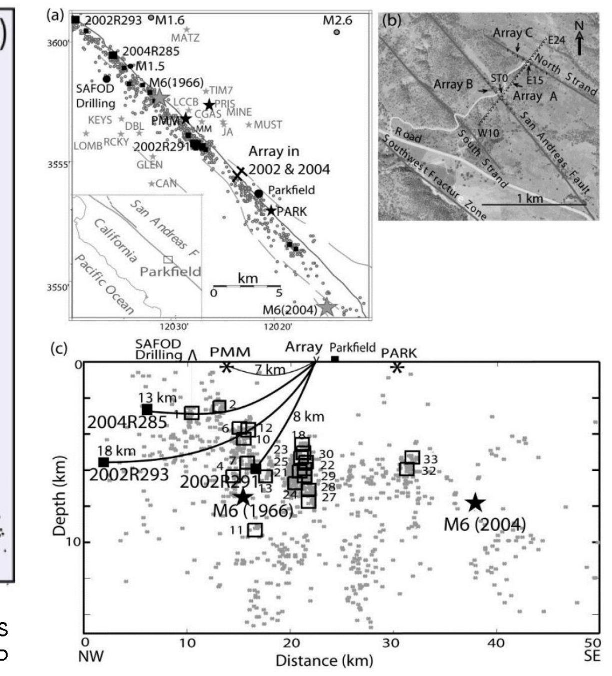


Fig.1 Right: (a) Map shows locations of seismic arrays repeatedly deployed at Parkfield SAF in 2002 and 2004. PMM – repeated shot. Dots - aftershocks of the 2004 M6 quake. Squares - 21 clusters, each including five repeated aftershocks which are similar to the earth quakes R291 and R293 in 2002.

Post-Seismic Heal of Rupture Zones after Lander and HM Earthquakes

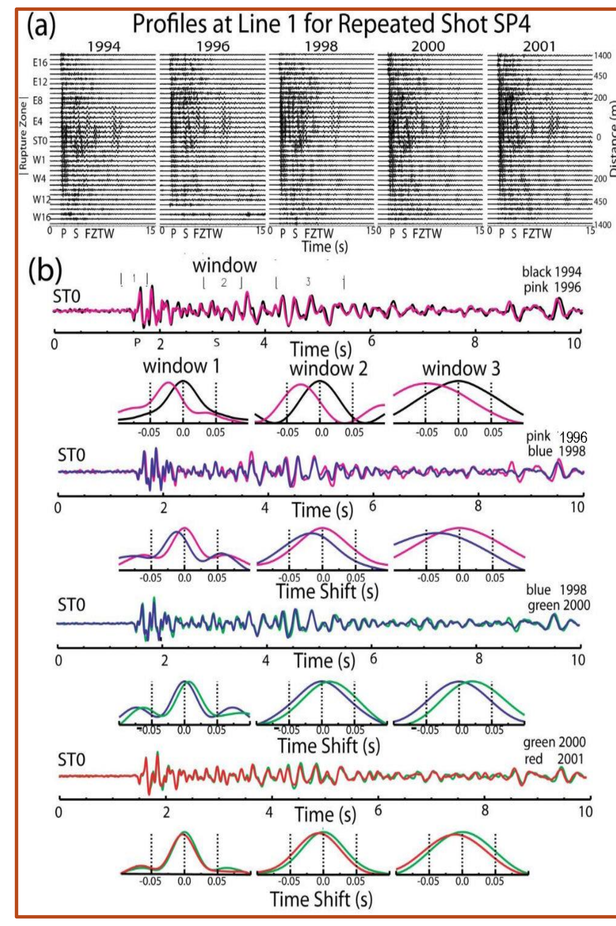
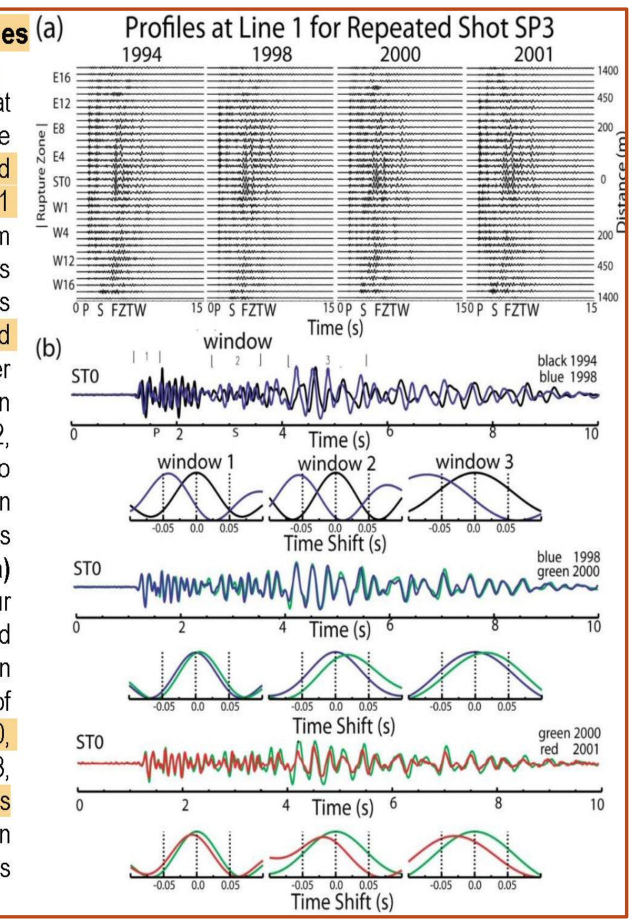
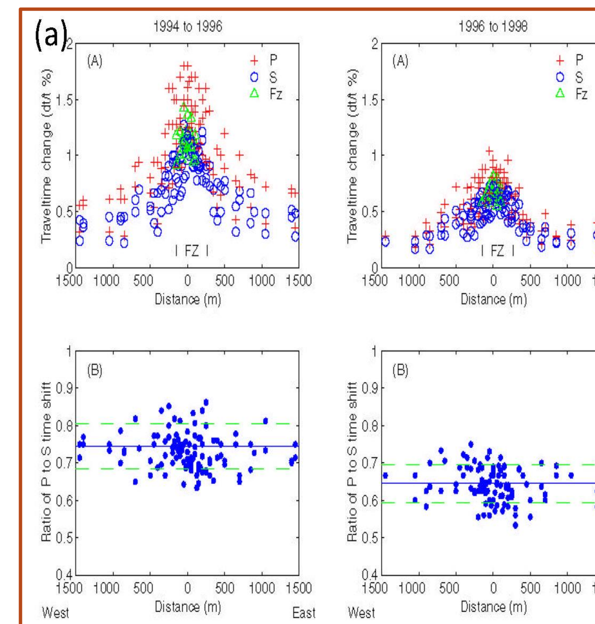


Fig.3 Left: (a) Seismograms recorded at Line 1 for shot SP4 detonated within the Landers rupture zone in five repeated experiments between 1994 and 2001 show similar waveforms. **(b)** Waveform cross-correlations in 3 time windows show that traveltimes of P, S, and FZTWs at station ST0 advanced by 26, 35, and 50 ms between 1994 and 1996, further decreased by 15, 25, and 35 ms between 1996 and 1998, but increased by 7, 12, and 16ms between 1998 and 2000 due to the nearby M7.1 HM earthquake, then decreased again by 7, 14, and 20ms between 2000 and 2001. **Right: (a)** Same as in top but for shot SP3 in four repeated experiments between 1994 and 2001.. **(b)** Waveform cross-correlations in 3 time windows show that traveltimes of P, S, and FZTWs at ST0 advanced by 40, 65, and 82 ms between 1994 and 1998, but increased by 8, 13, and 18 ms between 1998 and 2000, and then decreased again by 10, 20, and 25 ms between 2000 and 2001.





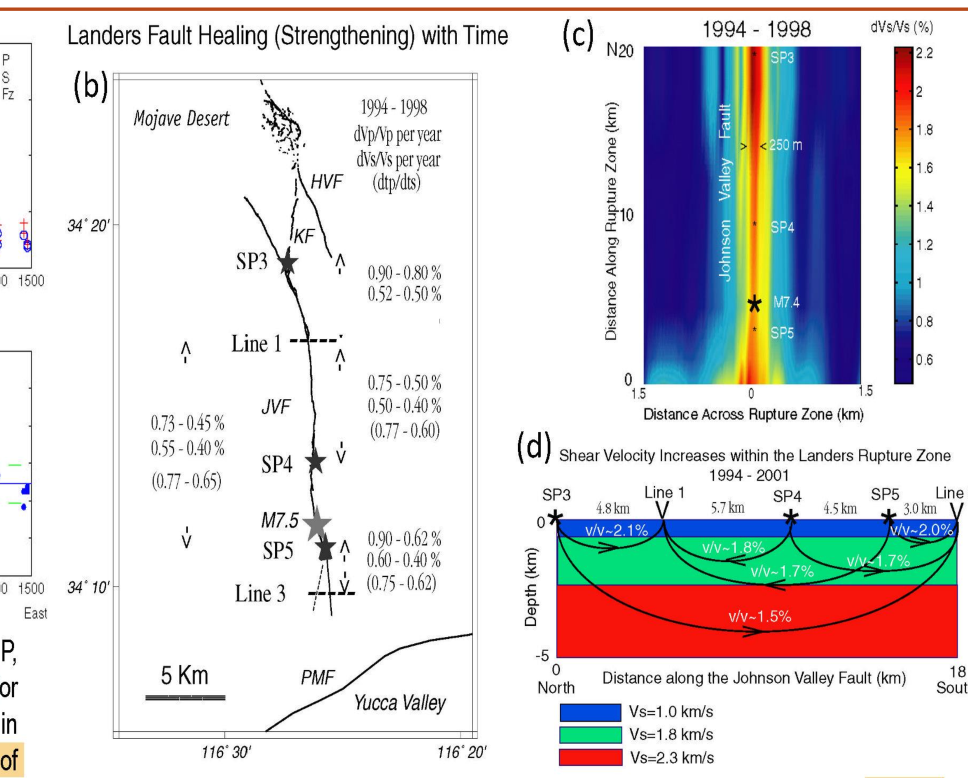


Fig. 8 (a) Summary of measured velocity increases of P, S and FZTWs recorded at all stations of Lines 1 and 2 for shots SP4 and SP5 in repeated experiments at Landers in 1994, 1996 and 1998, showing velocity increases of ~1.5% and ~1.1% between 1994 and 1996, and further increases of 0.8% and 0.5% for P- and S-waves within Landers rupture zone, while much smaller velocity increases out of the rupture zone. The Δtp/Δts ratio within the rupture zone was **~0.73** in average between 1994 and 1996, and reduced to **0.62** between 1996 and 1998.

(b) Map shows the velocity increases for P- and S-waves as well as the reduction of Δtp/Δts ratio (increasing of crake water saturation degree) measure 4 repeated shot-array pairs along Landers rupture zone between 1994 and 1998. **(c)** Map view shows the greater shear velocity increases within Landers rupture zone along the JVF between 1994 and 1998. **(d)** Depth-dependent shear velocity increases within rupture zone along the JVF in 1994-2001 show the larger healing rate at the shallower depth. .

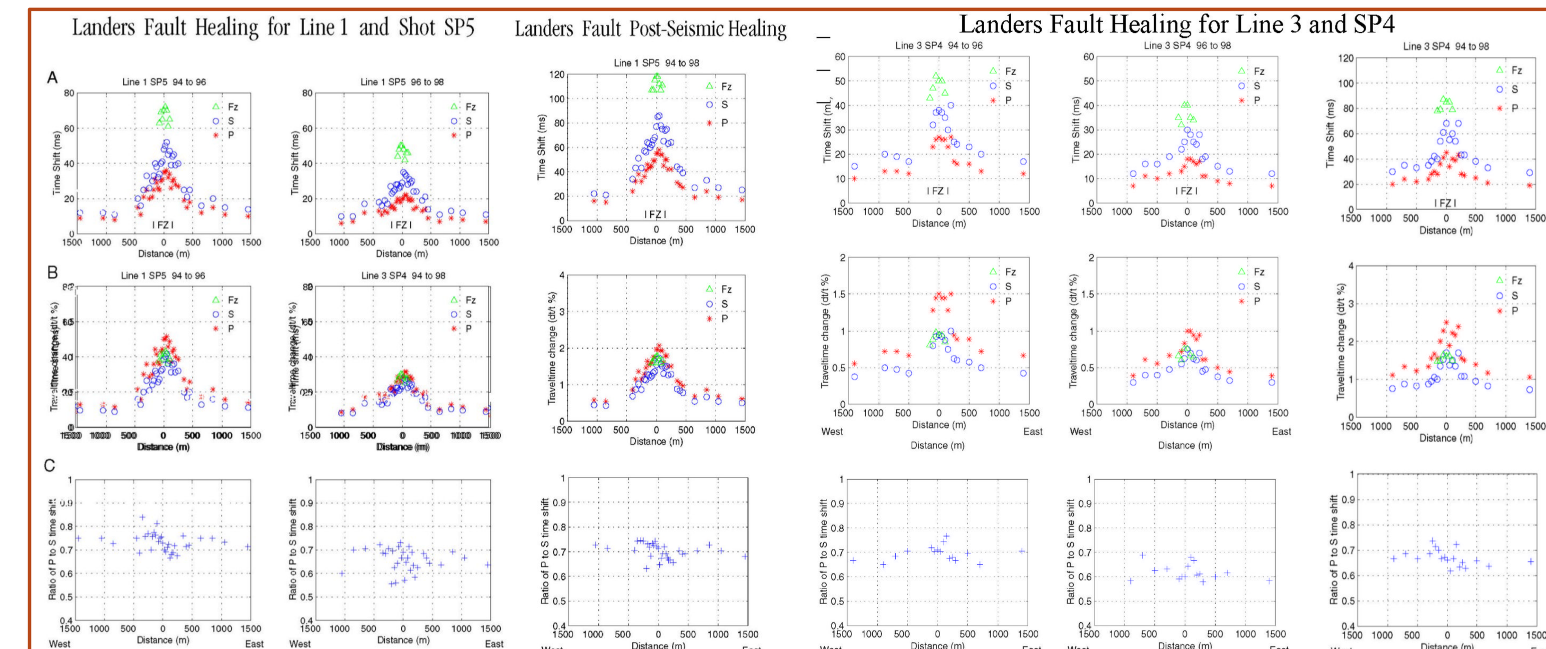


Fig. 7 Left: (A) Measured traveltime decreases and **(B)** velocity increases of P (red), S (blue) and FZTWs (green) recorded at stations of Line 1 for shot SP5 in repeated experiments at Landers between 1994, 1996 and 1998. **(C)** The Δtp/Δts ratio within the Landers rupture zone was **0.72** in average between 2 and 4 years after the 1992 M7.4 earthquake, and decreased to **0.62** between 4 and 6 years after the mainshock, suggesting that cracks within Landers rupture zone became apparently wetter with time, might either due to gradually closing of cracks which were co-seismically opened or post-seismically water filling into fault zone. **Right** Same as in left, but at Line 3 for shot 4 in repeated experiments in 1994, 1996 and 1998. The Δtp/Δts ratio within the southernmost Landers rupture zone was **0.7** in average between 2 and 4 years after the 1992 M7.4 earthquake, and decreased to **0.6** between 4 and 6 years after the mainshock, suggesting that cracks became apparently more wet within the southernmost rupture zone around the epicenter after the 1992 M7.4 mainshock.

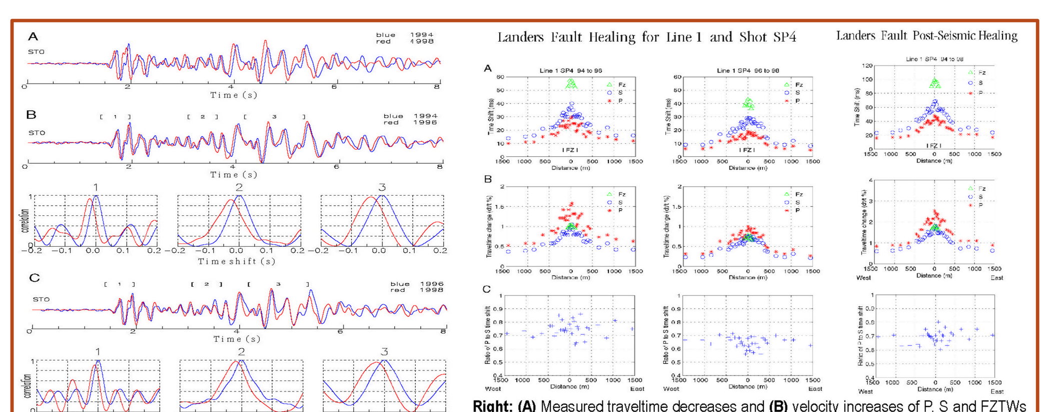


Fig.4 Left: Seismograms and waveform cross-correlations recorded at station ST0 of Line 1 for explosion SP4 detonated in 1994, 1996 and 1998 show that waves traveled faster with year. Traveltimes at ST0 decreaced by 26, 35 and 50 ms between 1994 and 1996, and by 15, 25, and 35 ms between 1996 and 1998, indicating that fault rocks damaged in the 1992 M7.4 mainshock were healing with time.

Right: (A) Measured traveltime decreases and **(B)** velocity increases of P, S and FZTWs recorded at Line 1 for shot SP4 detonated in repeated experiments at Landers in 1994, 1996 and 1996,. **(C)** The Δtp/Δts ratio within the Landers rupture zone was **0.75** in average between 2 and 4 years after the 1992 M7.4 earthquake, and decreased to **0.65** between 4 and 6 years after the mainshock, suggesting that cracks within Landers rupture zone became apparently wetter with time, might either due to gradually closing of cracks which were co-seismically opened or post-seismically water filling into fault zone. The Δtp/Δts ratio out of the rupture zone changed from ~0.85 to ~0.75 in this time period.

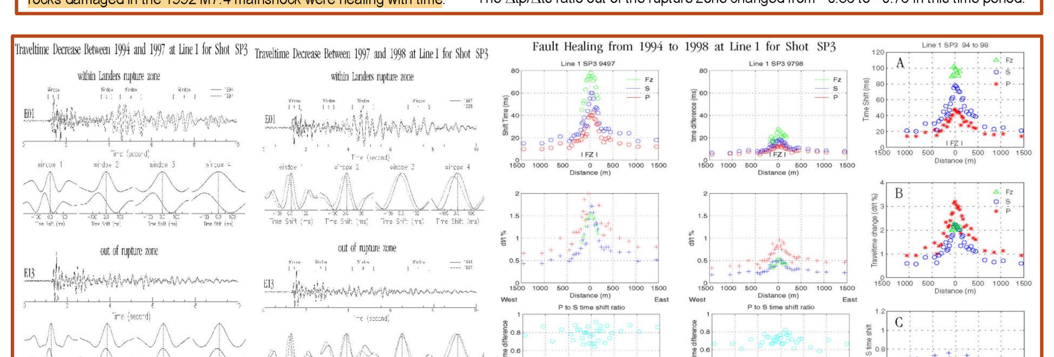


Fig. 5 Left: Seismograms recorded at stations E01 and E13 of Line 1 within and out of 200-m-wide rupture zone for explosion SP3 detonated in 1994, 1997 and 1998 show that seismic waves travel within Landers rupture zone faster with years, indicating that damaged rocks in the 1992 M7.4 mainshock healed with time. Cross-correlations of seismograms recorded at station E01 in 1994 and 1997 in 4 time-windows show traveltime decreases of 40, 65, 82 and 105 ms for P, S, and FZTWs between 1994 and 1997, and further by 15, 25, 35 and 45 ms between 1997 and 1998, but much small time decreases out of the rupture zone.

Right: Measured traveltime decreases and velocity increases of P, S and FZTWs recorded at Line 1 for shot 3 in repeated experiments at Landers in 1994, 1997 and 1998. The Δtp/Δts ratio within the Landers rupture zone was **0.78** in average between 1994 and 1997 after the 1992 M7.4 earthquake, and reduces to **0.68** between 1997 and 1998. The Δtp/Δts ratio out of the rupture zone changed from ~0.85 to ~0.75 in this time period.

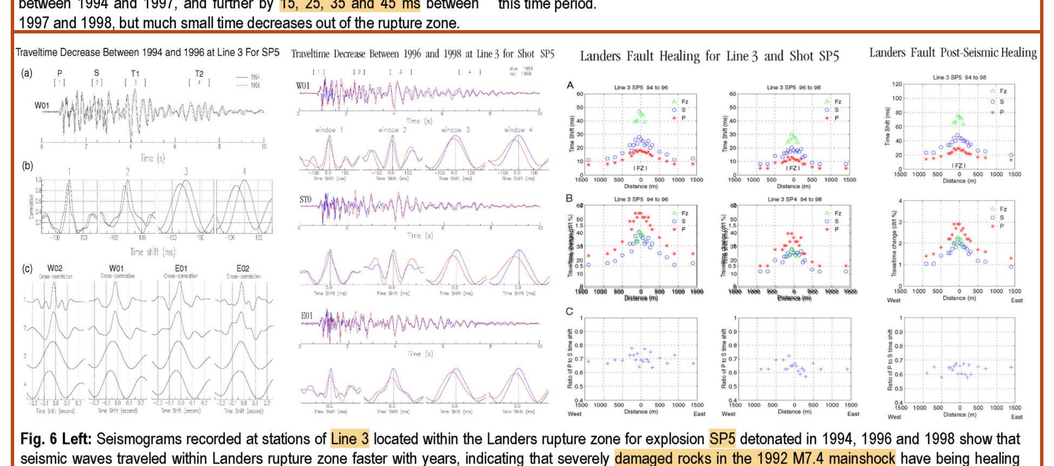
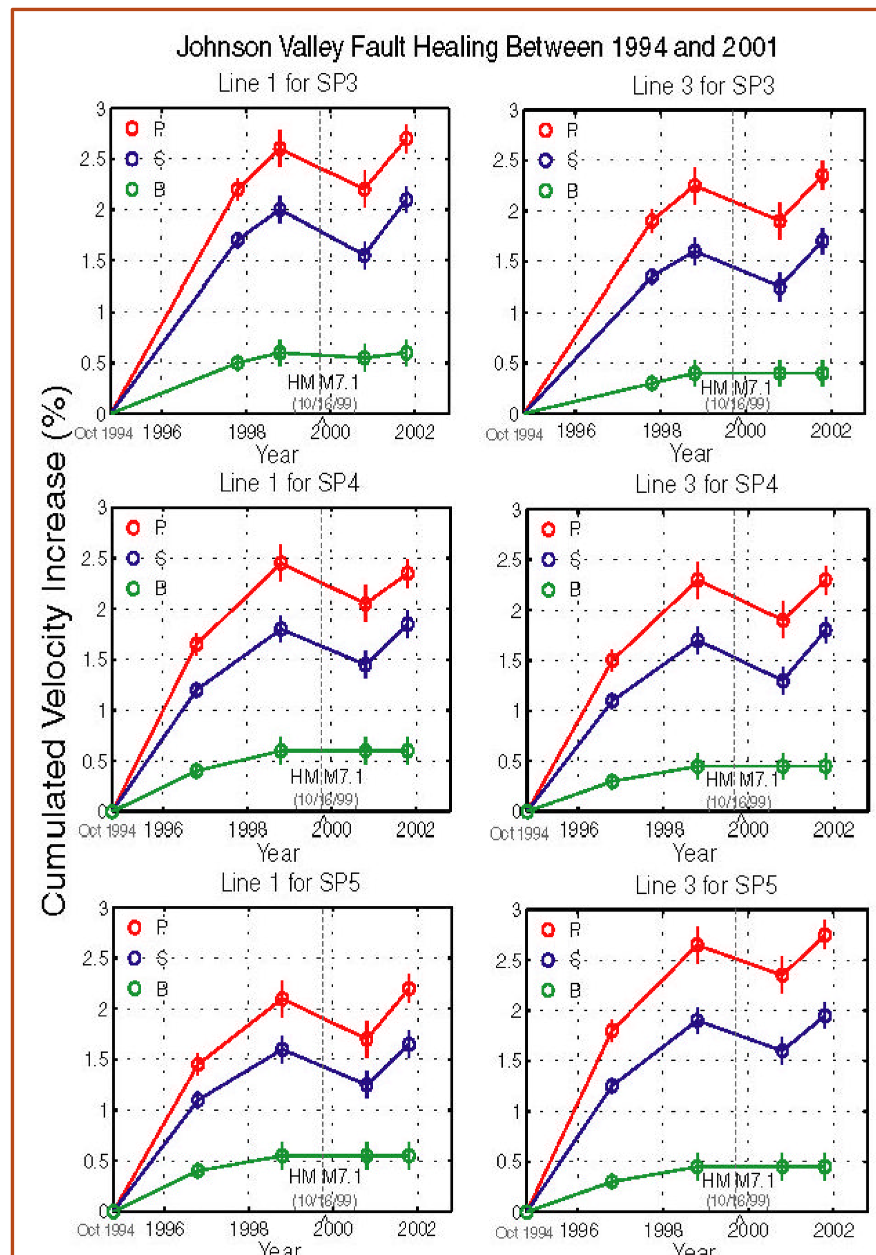


Fig. 6 Left: Seismograms recorded at stations of Line 3 located within the Landers rupture zone for explosion SP5 detonated in 1994, 1996 and 1998 show that seismic waves traveled within Landers rupture zone faster with years, indicating that severely damaged rocks in the 1992 M7.4 mainshock have being healing with time. Cross-correlations of seismograms recorded in 1994 and 1996 in 4 time-windows show time advances for P, S, and FZTWs between 1994 and 1996, and further advanced between 1996 and 1998 but with the lower rate. **Right:** Measured traveltime decreases and velocity increases of P, S and FZTWs recorded at Line 3 for shot 5 in repeated experiments at Landers between 1994 and 1997, and 1997 and 1998. The Δtp/Δts ratio within the southernmost Landers rupture zone was **0.7** in average between 2 and 4 years after the 1992 M7.4 earthquake and reduced to **0.6** in 2 year later, suggesting that cracks became apparently more wet within the rupture zone around the epicenter after the 1992 M7.4 mainshock.



Cumulated velocity changes of P velocity (red) and S velocity (blue) measured at 5 stations for 6 shot-array pairs within the Landers rupture zone between 1994 and 2001. Green symbols denote measurements at stations out of the fault zone.

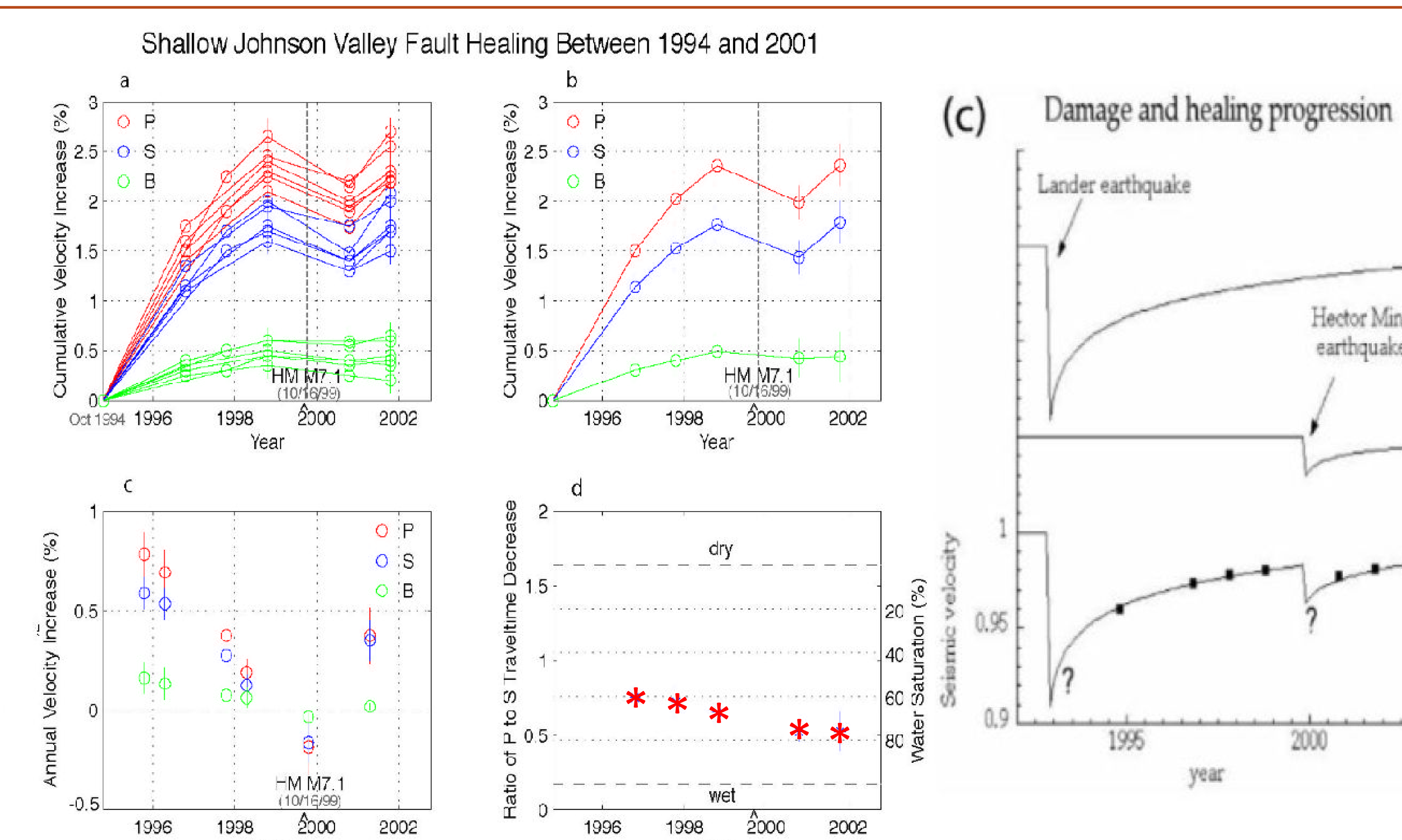


Fig. 9 (a) and (b) Cumulated velocity changes of Vp and Vs measured at stations within and outside rupture zone for 6 shot-array pairs in repeated experiments between 1994 and 2001 after the 1992 M7.4 Landers earthquake. **(c)** The annual increase in velocity, and **(d)** the Δtp/Δts ratios within the Landers rupture zone was **0.75** between 1994 and 1996, and decreased to **0.65** between 1996 and 1998 and further to **0.55** until 2001, suggesting that the apparent water-saturation degree of cracks within rupture zone increased with time after the mainshock. **(c)** Velocity as a function of time owing to damage from the Landers rupture and the HM shaking compared with observations. Heal is shown as a logarithm of time.