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Seismic Evidence for Rock Damage and Healing on the San Andreas Fault Associated with the 2004 M 6.0 Parkfield Earthquake

by Yong-Gang Li, Po Chen, Elizabeth S. Cochran, John E. Vidale, and Thomas Burdette

Abstract We deployed a dense linear array of 45 seismometers across and along the San Andreas fault near Parkfield a week after the **M** 6.0 Parkfield earthquake on 28 September 2004 to record fault-zone seismic waves generated by aftershocks and explosions. Seismic stations and explosions were co-sited with our previous experiment conducted in 2002. The data from repeated shots detonated in the fall of 2002 and 3 months after the 2004 **M** 6.0 mainshock show ~1.0%–1.5% decreases in seismic-wave velocity within an ~200-m-wide zone along the fault strike and smaller changes (0.2%–0.5%) beyond this zone, most likely due to the coseismic damage of rocks during dynamic rupture in the 2004 **M** 6.0 earthquake. The width of the damage zone characterized by larger velocity changes is consistent with the low-velocity waveguide model on the San Andreas fault, near Parkfield, that we derived from fault-zone trapped waves (Li *et al.*, 2004). The damage zone is not symmetric but extends farther on the southwest side of the main fault trace. Waveform cross-correlations for repeated aftershocks in 21 clusters, with a total of ~130 events, located at different depths and distances from the array site show ~0.7%–1.1% increases in *S*-wave velocity within the fault zone in 3 months starting a week after the earthquake. The velocity recovery indicates that the damaged rock has been healing and regaining the strength through rigidity recovery with time, most likely due to the closure of cracks opened during the mainshock. We estimate that the net decrease in seismic velocities within the fault zone was at least ~2.5%, caused by the 2004 **M** 6.0 Parkfield earthquake. The healing rate was largest in the earlier stage of the postmainshock healing process. The magnitude of fault healing varies along the rupture zone, being slightly larger for the healing beneath Middle Mountain, correlating well with an area of large mapped slip. The fault healing is most prominent at depths above ~7 km.

Introduction

Extensive field and laboratory research and numerical simulations indicate that the fault zone undergoes high, fluctuating stress and pervasive cracking during an earthquake (e.g., Dieterich, 1978; Aki, 1984; Scholz, 1990; Rice, 1992; Kanamori, 1994). While we know slip is localized on faults because of their lower strength compared to the surrounding bedrock, critical parameters remain practically unknown (e.g., Sleep *et al.*, 2000). For example, the friction laws are approximate, and damage and healing rates are poorly constrained (e.g., Richardson and Marone, 1999; Morgan, 2004). Perhaps most critically, the magnitude of the strength reduction and its spatial extent has only been measured partially and at a few places before (e.g., Hickman and Evans, 1992; Vidale *et al.*, 1994). Earthquake-related fault-zone damage and healing have been documented quantitatively in only a few cases (e.g., Marone *et al.*, 1995; Li *et al.*, 1998, 2003; Massonnet *et al.*, 1996; Yasuhara *et al.*, 2005). In order to relate present-day crustal stresses and fault motions to the geological structures formed in their past earthquake histories, we must understand the evolution of fault systems on many spatial and time scales. Major crustal faults are structurally marked by zones of lowered velocity with a width of a few hundred meters to a few kilometers (Mooney and Ginzburg, 1986). Intense fracturing during earthquakes, brecciation, liquid-saturation, and possibly high pore-fluid pressure near the fault are thought to create these low-velocity zones. The size and magnitude of the low-velocity anomalies on active faults might vary over the earthquake cycle, as observed in our previous studies at rupture zones of the 1992 *M* 7.4 Landers and 1999 *M* 7.1 Hector Mine, California earthquakes (Li *et al.*, 1998, 2003; Li and Vidale, 2001; Vidale and Li, 2003).

Research at the San Andreas fault (SAF) at Parkfield has revealed a low-velocity zone a few hundred meters to 1 km