SCEC3 Research and Outreach Activity Report

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Summary

Funding from SCEC3 in 2011 has contributed to supporting three studies of the earthquake cycle at the Parkield segment of the San Andreas Fault. In a first study, we have looked at the postseismic relaxation following the 2004 Mw 6 Parkfield, CA earthquake using GPS and Interferometric Synthetic Aperture Radar (InSAR) data (*Bruhat et al.*, 2011). We have shown that the surface deformation is dominantly explained by afterslip around the coseismic rupture with a possible contribution of distributed viscoelastic flow in the lower crust. This study highlights the variations of the degree of localization of deformation at crustal depths. This study has been executed by a visiting undergraduate student, Lucile Bruhat, with the co-mentoring of post-doctoral fellow Sylvain Barbot. In a second study partially funded by SCEC3, we have developed a physical model of the earthquake cycle at Parkfield with rate-and-state friction (*Barbot et al.*, 2012b). The model consists of a spatial distribution of friction property which is tuned to explain a variety of seismological, geodetic and paleoseismic observations. The model generates spontaneous ruptures between longer periods of quasi-static loading and reproduces the average recurrence time, the magnitude and hypocenters of the latest moderate-size earthquakes at Parkfield. In particular, we have found that the change of hypocenter location of the Mw 6 earthquakes from the north in 1966 to the south in 2004 can occur spontaneously on rate-and-state friction faults due to a complexity in the history of faulting. This study was performed in collaboration with Prof Nadia Lapusta and is to be published in Science this year. Lastly, the SCEC3 founding has allowed us to use InSAR and GPS data, in combination to results from seismological investigations, to check whether or not the seismogenic zone at Parkfield is surrounded by persistent streaks of seismicity (*Barbot et al.*, 2012a). We have found that this scenario is plausible, i.e., not in contradiction with the geodetic data. But more importantly, we have established that augmenting the Plate Boundary Observatory (PBO) GPS network with 20 additional stations - if optimally situated - would allow us to monitor slip in the seismogenic zone with sufficient resolution. These studies provide a self-consistent physical interpretation of the earthquake cycle at Parkfield and motivate further targeted investigations, part of the new Parkfield Special Fault Study Area of SCEC4.

Evidence for postseismic deformation of the lower crust following the 2004 Mw 6.0 Parkfield earthquake

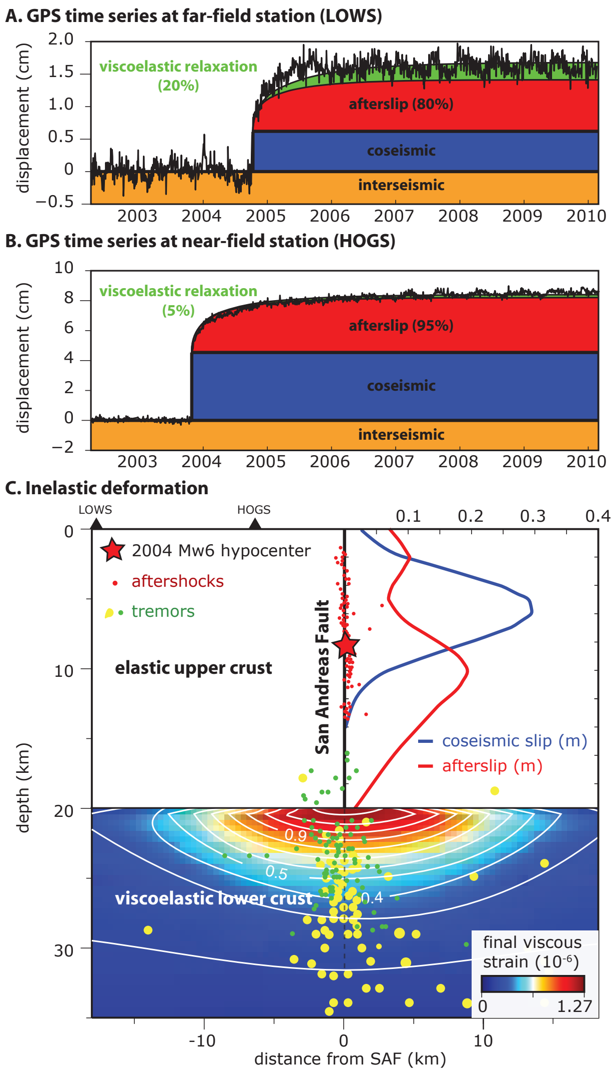

Figure 1: Relative contribution of afterslip and viscoelastic flow for near-field (A) and far-field (B) GPS stations. C) Depth-averaged coseismic slip and afterslip and cumulative viscous strain $\gamma(\mathbf{x}) = \int_0^\infty ||\boldsymbol{\epsilon}^i(\mathbf{x},t')||dt'$ in the viscoelastic substrate across the fault. The integrated strain corresponds to 2 cm of viscous displacement across the fault distributed over 20 km (*Bruhat et al.*, 2011).

Several studies have shown that postseismic relaxation following the 2004 Mw 6.0 Parkfield, CA earthquake is dominated by afterslip. However, we show that some fraction of the afterslip inferred from kinematic inversion to have occurred immediately below the seismically ruptured area may in fact be a substitute for viscous postseismic deformation of the lower crust (*Bruhat et al.*, 2011). Using continuous GPS and InSAR, we estimate the relative contribution of shallow afterslip (at depth less than 20km) and deeper seated deformation required to account for observed postseismic surface displacements. Exploiting the possible separation in space and time of the time series of displacements predicted from viscoelastic relaxation, we devise a linear inversion scheme that allows inverting jointly for the contribution of afterslip and viscoelastic flow as a function of time. We find that a wide range of models involving variable amounts of viscoelastic deformation can fit the observations equally well provided that they allow some fraction of deep-seated deformation (at depth larger than $\sim$ 20 km). All the models show a remarkable complementarity of coseismic and shallow afterslip distributions. Some significant deformation at lower crustal depth (20-26 km) is required to fit the geodetic data. The condition that postseismic deformation cannot exceed complete relaxation places a constraint on the amount of deep seated deformation. The analysis requires an effective viscosity of at least $\sim 10^{18}$ Pa s of the lower crust. This deep-seated deformation is consistent with the depth range of tremors which also show a transient postseismic response. Lower crustal postseismic deformation could reflect a combination of localized ductile deformation and aseismic frictional sliding (Fig. 1).

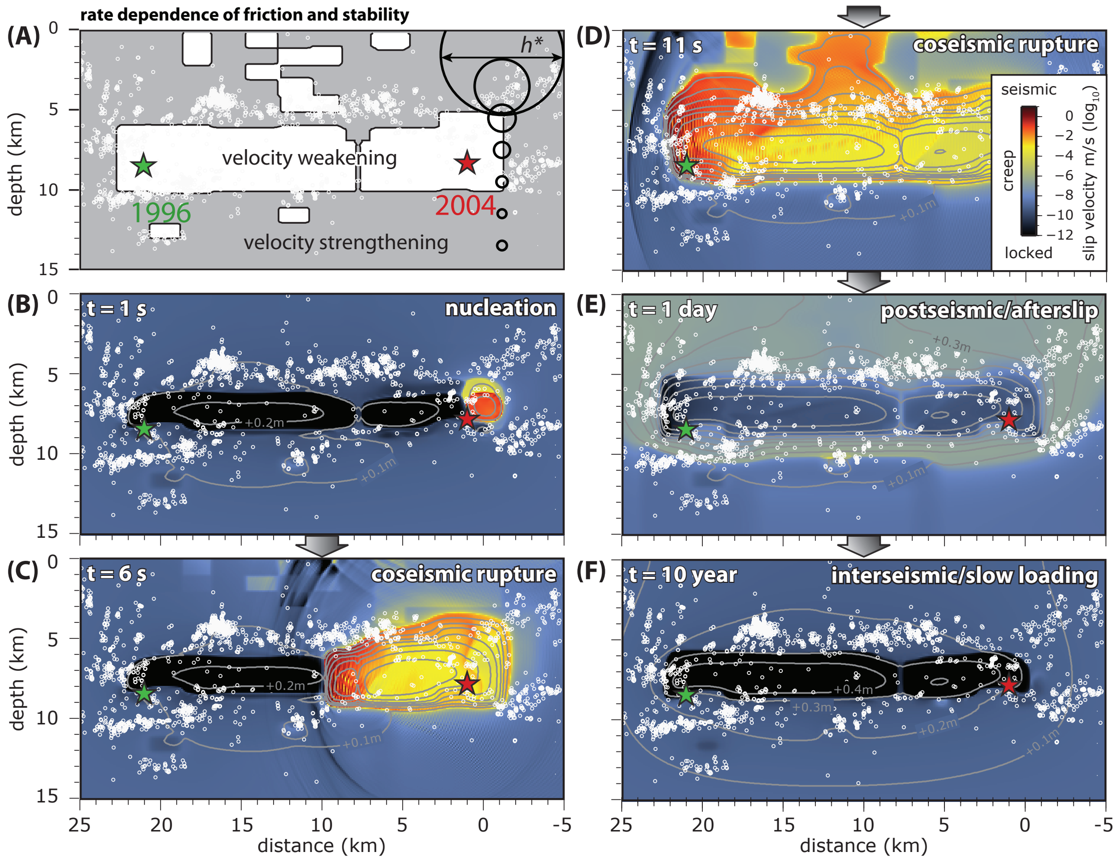

Figure 2: Model that reproduces the entire seismic cycle at Parkfield. A) Spatial distribution of rate-weakening (white) and rate-strengthening (grey) friction properties $(a-b)$, with rate-weakening values in the seismogenic zone, delineated by the background seismicity. B-F) Snapshots of a Mw 6.0 seismic cycle with rupture nucleating spontaneously to the south, near the Parkfield 2004 hypocenter. Another Mw 6 event nucleates 20 years later.

Under the Hood of the Earthquake Machine

Seismic and geodetic observations provide an increasingly detailed insight into the fault motion over a wide range of temporal and spatial scales, from rapid seismic rupture to slower postseismic slip and complex interseismic behavior, including slow episodes of accelerating slip and tremor. Yet, models capable of capturing a wide range of such observations for a given fault zone in space and time are largely missing. Existing models, while quite useful and advanced in their own right, are either restricted to specific aspects of fault behavior - progression of a single dynamic rupture, evolution of postseismic slip - or simplify some stages of the fault deformation, e.g. by excluding wave-mediated effects during seismic slip. At the same time, laboratory experiments and theoretical developments provide an increasingly realistic and detailed understanding of the fault physics, offering the basis for inferring fault properties from seismic and geodetic observations. Furthermore, recently developed numerical methods allow to resolve, in one physical model, slow tectonic loading, earthquake nucleation, and rupture propagation - including the radiation of seismic waves - and the afterslip transient that follows main shocks. Here, we develop the first fully dynamic model of the earthquake cycle capable of quantitatively reproducing a wide range of observations for the Parkfield segment of the San Andreas Fault (Fig. 2). Our study demonstrates the possibility of creating comprehensive physical models of fault zones that integrate geodetic and seismological observations for all stages of the earthquake source cycle. As computational resources and methods improve, more realistic fully dynamic simulations - allowing for a wider range of earthquakes magnitude occurring on a set of interacting faults - will become possible. Such simulations could in principle be used to assess the full range of earthquake patterns that a particular fault system might produce, or assimilate observation about past earthquakes and interseismic loading to assess future seismicity.

Geodetic Constraints on the Parkfield Seismogenic Zone: Implications for the Earthquake Prediction Experiment

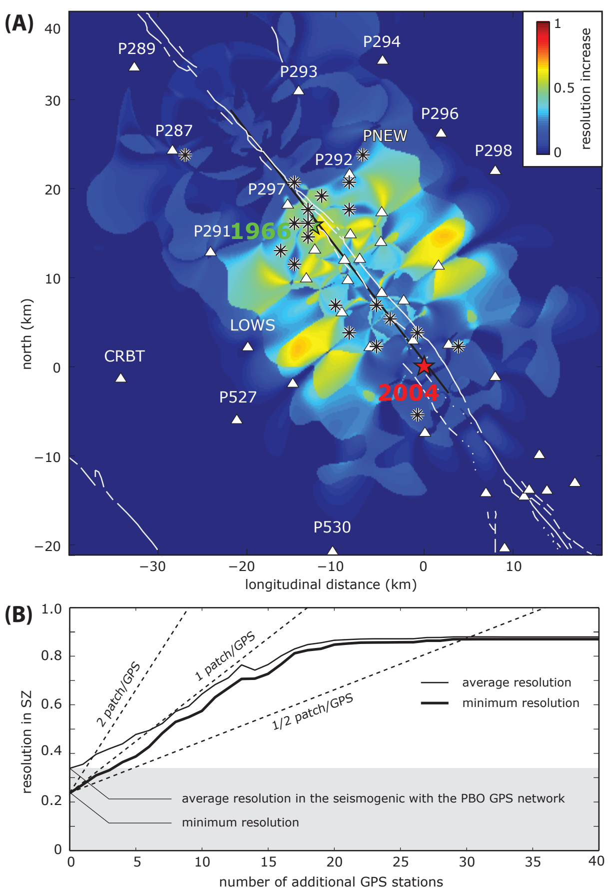

Figure 3: Experiment design to monitor the seismogenic zone geodetically. A) Map view of the resolution increase of a potential new GPS station and location of the optimal distribution of new stations (black stars). B) Efficiency of the optimal network based on the number of stations added. Optimally planned, only 20 new stations are needed to resolve 2×2 km patches in the seismogenic zone with a minimum 0.8 resolution.

Accurate relocation of microseismicity on the Parkfield segment of the San Andreas Fault in California reveals a clustering of repeating micro-earthquakes with a highly organized spatio-temporal distribution of hypocenters. In general, areas devoid of microseismicity are suggestive of zones with somewhat homogeneous friction properties, either aseismic or seismogenic. The presence of the hypocenters of the 1966 and the 2004 Mw 6 Parkfield earthquakes in a large seismically quiet zone at about 7 km depth indicates that the seismic streaks may delineate the contours of the seismogenic zone. Among various inferences of slip from seismological data, some place most of the coseismic slip in the area of the fault circumscribed by background seismicity. However, inversions for coseismic slip from geodetic data from various investigators show a less obvious correlation between slip and the distribution of microearthquakes. We test a couple of methods to improve the resolution of slip inversions from geodetic data. One is to optimize the sampling of the fault plane to reduce the tradeoffs between adjacent slip patches; another is to assimilate data from the interseismic period and require complementary slip distributions of interseismic creep and coseismic slip. Using the proposed methods, we reconcile inversions for coseismic slip from geodetic and seismological data and show that GPS and InSAR are compatible with the interpretation that the streaks of microseismicity circumscribe the seismogenic zone at Parkfield. This result suggests that the San Andreas Fault at Parkfield is partitioned into areas of stable and unstable friction delineated by enduring clusters of seismicity and that the transition occurs over a distance characterized by a concentration of microseismicity. The augmentation of the GPS network after the 2004 event allows us to better constrain fault slip, but more coverage is needed at strategic points to detect anomalous, and perhaps precursory, fault slip in the seismogenic zone during the current interseismic period before any future Mw 6 Parkfield rupture. We find the optimal spatial distribution of the additional GPS stations that will be required to resolve the seismogenic zone geodetically (Fig. 3).

Outreach

The Tectonics Observatory (TO) is committed to participate actively in the broader community. The recent and forthcoming events are listed at *http://www.tectonics.caltech.edu/*. Educational resources are available of the observatory's web site with research highlights - movies and short stories on ground-breaking TO research -, various animations and graphics (mountain building, seismic cycle and production of tsunamis, formation of the Grand Canyon rock layers). We participate in K-12 education by providing teaching material (paper model of earthquake fault, presentation on erosion, documentary film about science, video: how tectonics shaped Southern California, "mini-lessons" for undergraduate classes), organizing local geology excursions and meeting the local students in the class room or chatting with more remote students on Skype. We regularly host a tour of the TO for local 6th graders. The TO provides undergrad research opportunities.

References

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