Under the hood of the earthquake machine: towards predictive modeling of fault slip

Sylvain Barbot[1,3], Nadia Lapusta[1,2,3] and Jean-Philippe Avouac[1,3]

[1] Tectonics Observatory, California Institute of Technology, [2] Mechanical and Civil Engineering, [3] Seismological Laboratory, Caltech

Abstract

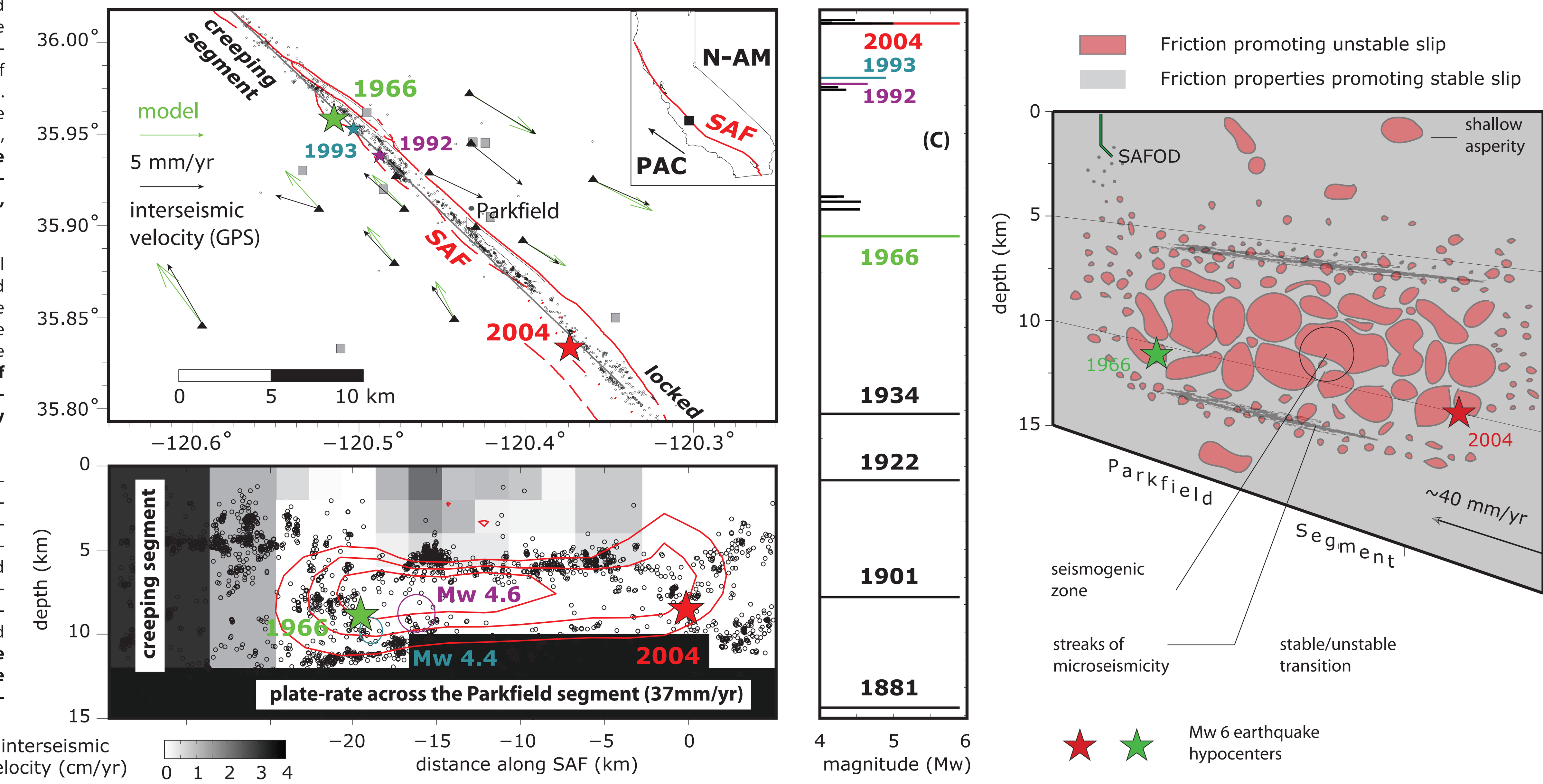
Recent advances in observations have highlighted fault behavior over different temporal scales, from rapid seismic motion to slower postseismic slip, and complex interseismic behavior, including episodic phases of accelerated slip. Many observations document complex spatial variations of faulting encompassing steady and oscillatory creep, unstable sliding, and more recently deep tremors. The difficulty to simulate realistic earthquake cycles in space and time can be attributed to the large and essentially unknown spatial variations in fault properties, a limited detailed history of past events and to the nonlinear friction law that controls fault dynamics. However, laboratory experiments and theoretical developments provide an increasingly realistic and detailed understanding of the fault physics, offering the basis for an extrapolation to natural conditions. **Here, we bridge the gap between observations and fault physics by developing the first model of the earthquake cycle to explain many puzzling, yet robust observations of the crustal dynamics at Parkfield.**

The Parkfield segment of the San Andreas Fault (SAF) is an ideal natural laboratory to model the earthquake cycle because of its rich behavior and the presence of an unprecedented array of observations, including the SAFOD drilling site and modern seismic and geodetic networks. Despite the similarities between the previous events and their short recurrence times (from 12 to 32 years for 5 events until 1966), **the latest rupture of 2004 defied the statistics by taking place a decade later than anticipated and initiated to the south to propagate northward, contrarily to all previous events**.

We present the first physical model of the full earthquake cycle at Parkfield that includes all stages of the deformation and reconciles many important observations while incorporating realistic aspects of fault dynamics. Our model is compatible with the contemporary relative motion between the North-American Plate and the Pacific Plate across the SAF and gives rise to a sequence of Mw 6 earthquakes that can explain the observed variability of hypocenters and reproduce the geodetic observations of surface deformation in the co- and postseismic periods associated with the 2004 event. **Our study introduces a methodology to integrate seismological and geodetic observations into a physical model of the earthquake cycle that can help better understand and mitigate seismic hazard around active faults.**

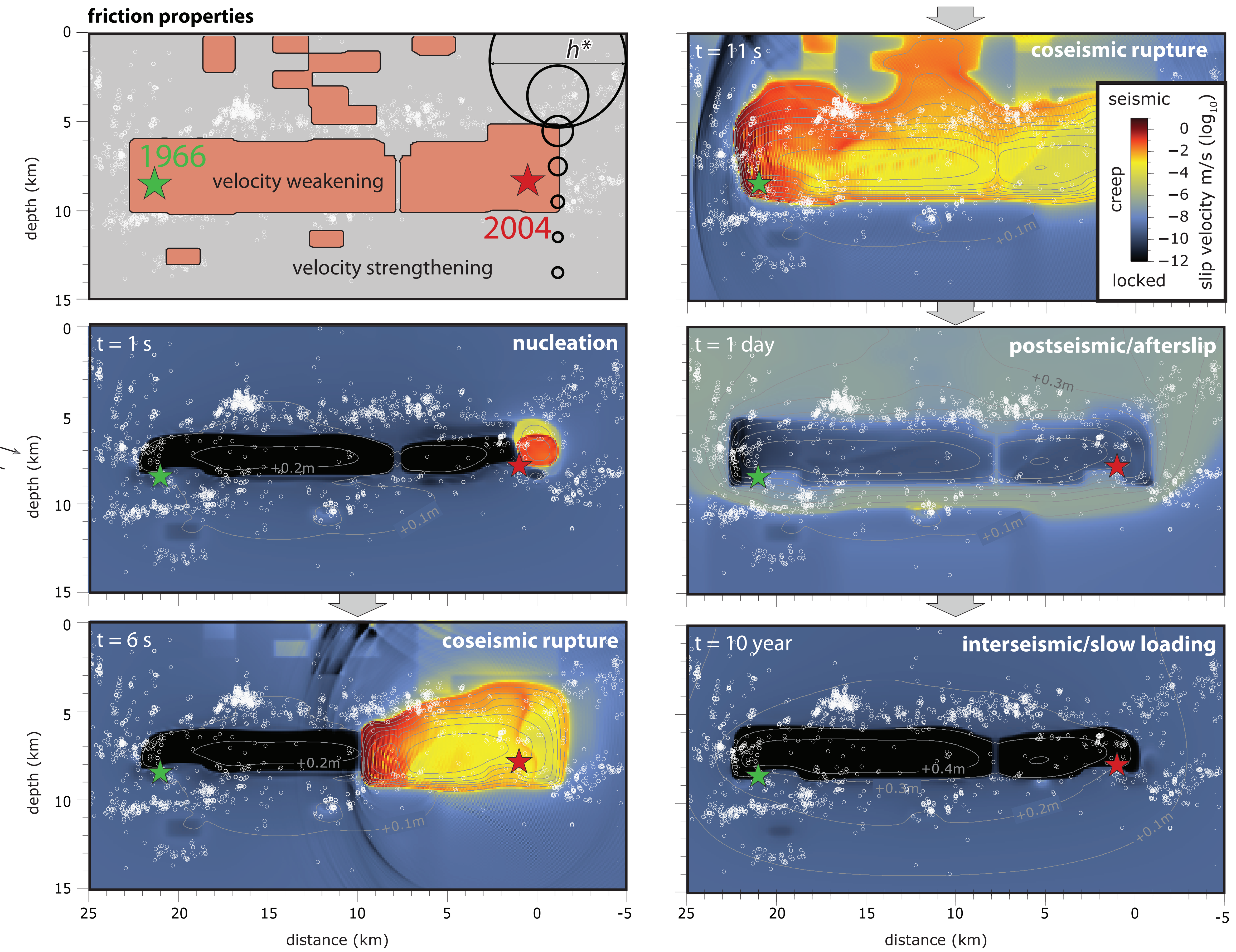
The special role of microseismicity at Parkfield: marking the locked/creeping transition

Our interpretation of the microseismicity circumscribing the SZ reconciles various observations of the earthquake cycle at Parkfield such as the inferred slip distributions of the 2004 earthquake from seismic and geodetic data, the secular GPS velocity, and our best estimate of the slip distribution for the 1966 earthquake. We terminate the SZ to the south close to the nucleation site of the 2004 event assuming that the hypocenters of moderate-size earthquakes are located in areas of stress concentration which can occur between stable and unstable friction.



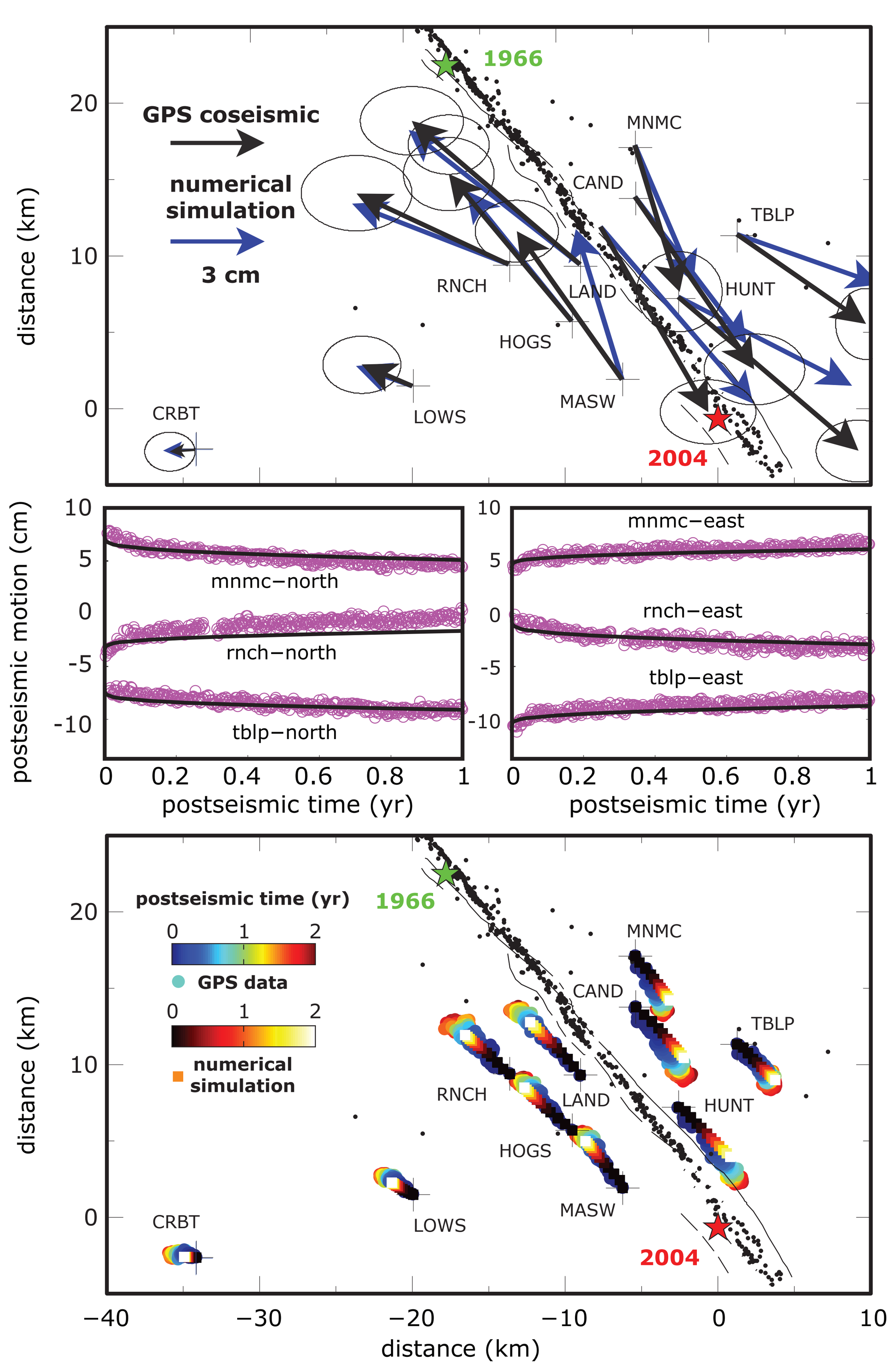
A reference model for the sequence of Mw 6 earthquakes at Parkfield

We obtain a long and rich history of fault slip with spontaneous nucleations and ruptures of earthquakes of magnitude ranging from Mw 2 to 6. The minimum size of simulated earthquakes in our models is bounded by finite computational resources and smaller earthquakes could be obtained on a finer numerical mesh. Some snapshots illustrative of the modeled fault dynamics are shown below for the case of a typical Mw6 earthquake, for which most coseismic slip occurs in the area circumscribed by microseismicity.



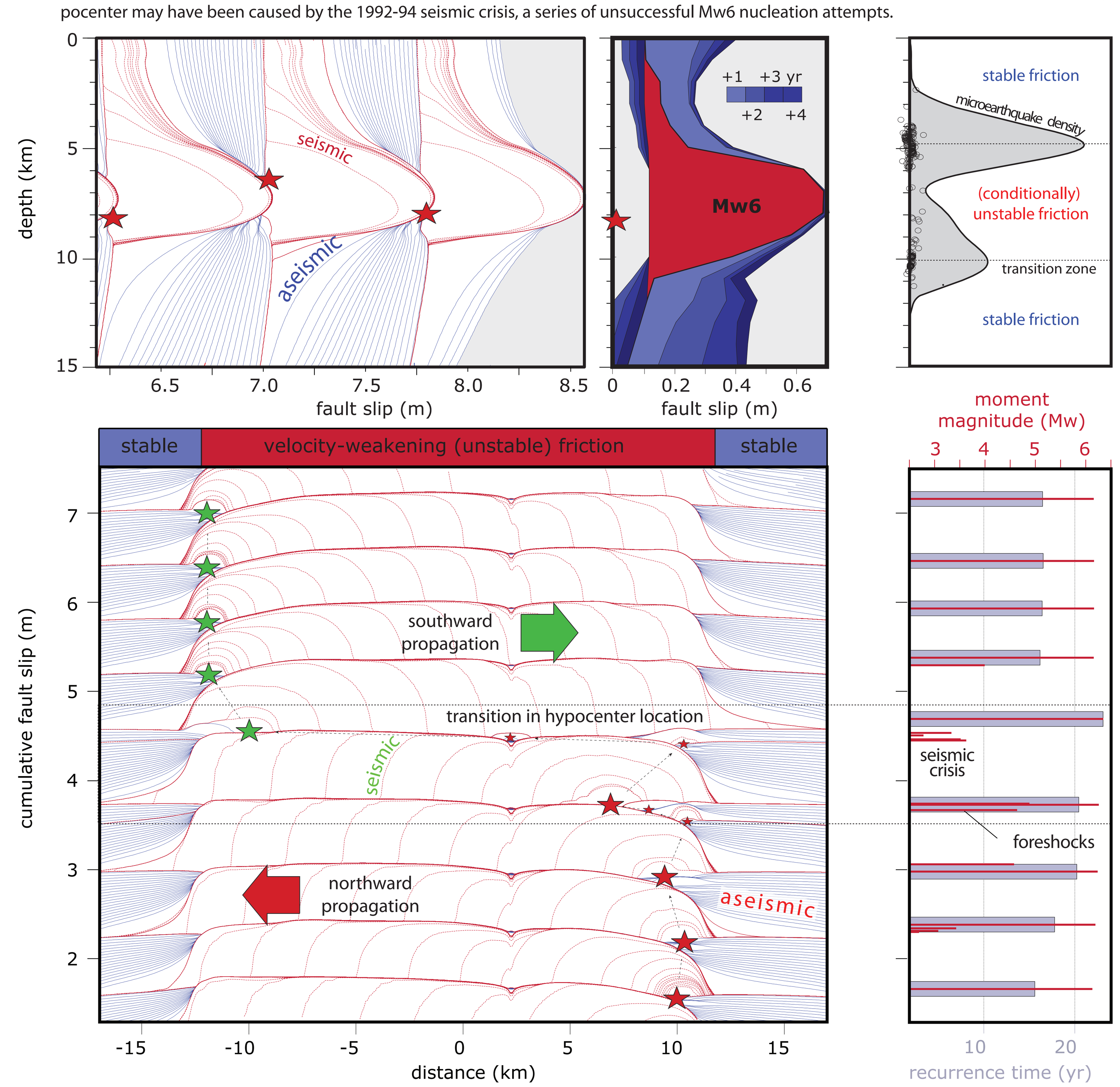
A physical model of the co- and postseismic deformation

Our fully dynamic model of the earthquake cycle offers an excellent fit to the coseismic GPS displacement vectors and the daily time series of postseismic GPS displacement.



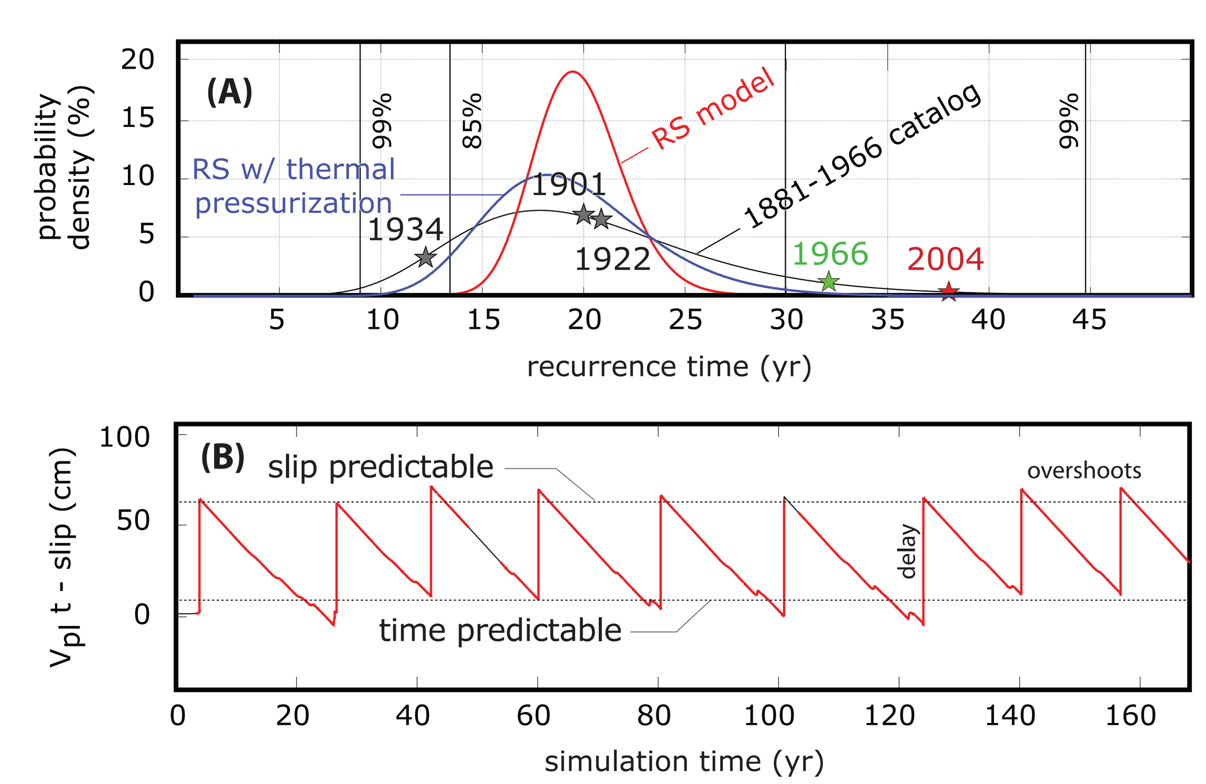
The delay of the 2004 event, the change of hypocenter, and the 1992-1994 seismic crisis

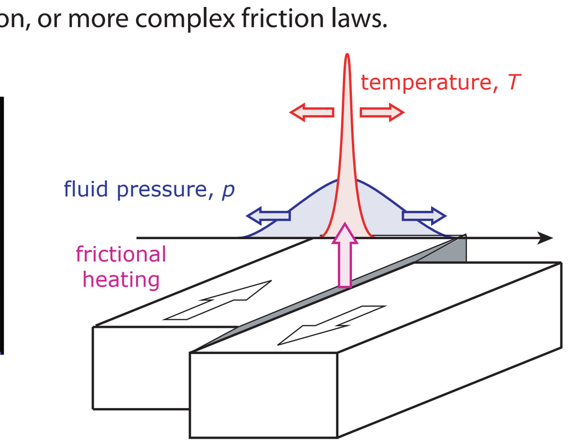
A change of hypocenter location and a delayed rupture together can result from a spontaneous behavior of rate-and-state friction faults, after a complex sequence of foreshocks and smaller interseismic events. The delay of the latest Mw6 2004 event at Parkfield and its unexpected change of hypocenter may have been caused by the 1992-94 seismic crisis, a series of unsuccessful Mw6 nucleation attempts.



Variability in recurrence times: New constraints on fault friction?

Rate-and-state friction models can offer a rich history of faulting and explain many aspects of the earthquake cycle at Parkfield. However, even more complex models may be required to explain the statistics of recurrence times and the large variability characteristic of the catalog of historical Mw6 earthquakes. Our model can offer a realistic variability in recurrence times and moments of Mw 6 earthquakes and explain some of the spread of the Parkfield catalog. A better understanding of the large contrasts of the observed recurrence times since 1881 may require taking into account more aspects of fault dynamics, including stress transfers from remote earthquakes, effect of the deeper parts of the fault, fine-grain variations of fault friction, or more complex friction laws.





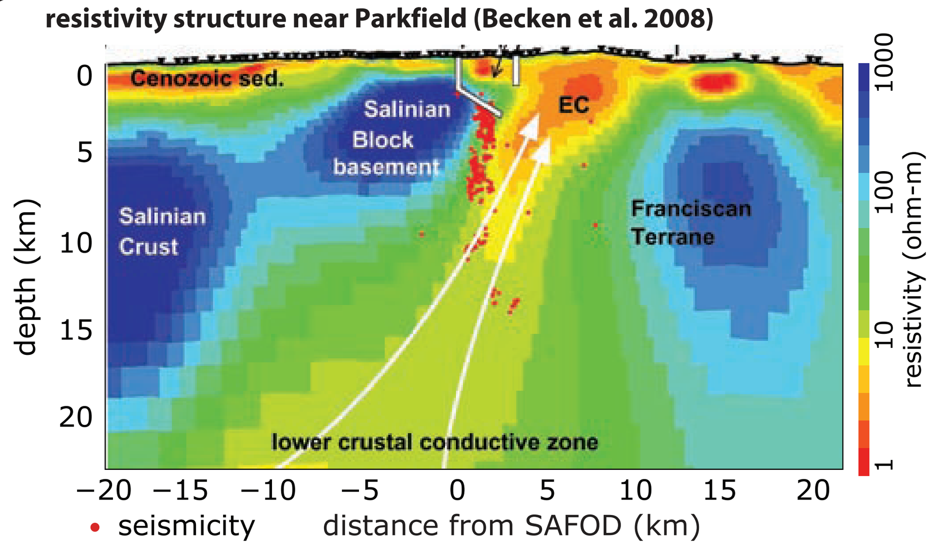
Results from resistivity experiments of high-resolution seismic tomography (Thurber et al. 2006) may indicate the presence of fluids on the San Andreas Fault at seismogenic depth. Accounting for pore fluid pressurization and induced fault weakening in our model gives rise to an irregular recurrence time in agreement with the paleoseismic catalog.

Thermal pressurization

Rapid shear heating during seismic slip increases fault temperature and may increase the pore fluid pressure leading to an additional mechanism for coseismic fault weakening

$$V = 2V_0\,\theta^{-b/a}\sinh\frac{\tau}{a(\sigma_n - p)}$$

resistivity structure near Parkfield (Becken et al. 2008)



Reference

Barbot S., N. Lapusta, J.-P. Avouac, "Under the Hood of the Earthquake Machine: Toward Predictive Modeling of the Seismic Cycle", Science, v. 336 (6082), p. 707-710, 2012

Conclusions

Our results indicate that the Dieterich-Ruina friction law can explain many aspects of faulting at the Parkfield segment of the San Andreas Fault. The change of hypocenter between 1966 and 2004 and the delay of the latest event is consistent with the occurrence of a swarm of smaller magnitude earthquakes during the 1992-1994 period. The proposed approach is applicable to other fault systems and can serve as an important tool to investigate the effect of other components of earthquake physics, such as thermal pressurization and triggering.