The San Andreas Fault in fine detail: seismology and rock physics

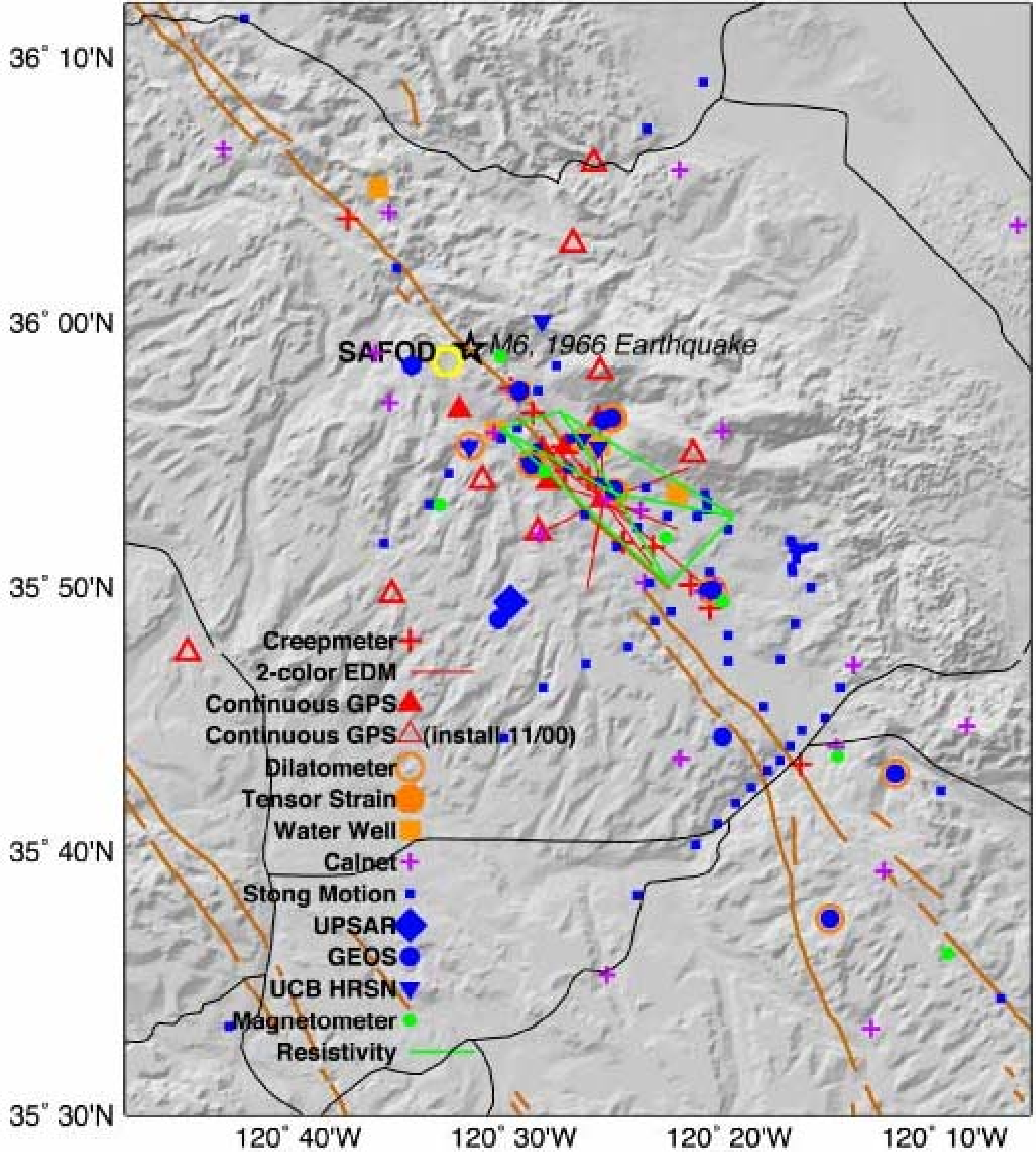
Feature instead of technique

- Tectonics Setting
  - Boundary between North American and Pacific Plates
  - Right-lateral strike-slip
- Focus on Parkfield region
  - Recurring earthquakes, mag 6 recur @22 yr intervals
  - Extensively instrumented with surface seismometers
  - SAFOD drilling program into the fault at depth

www.geology.com

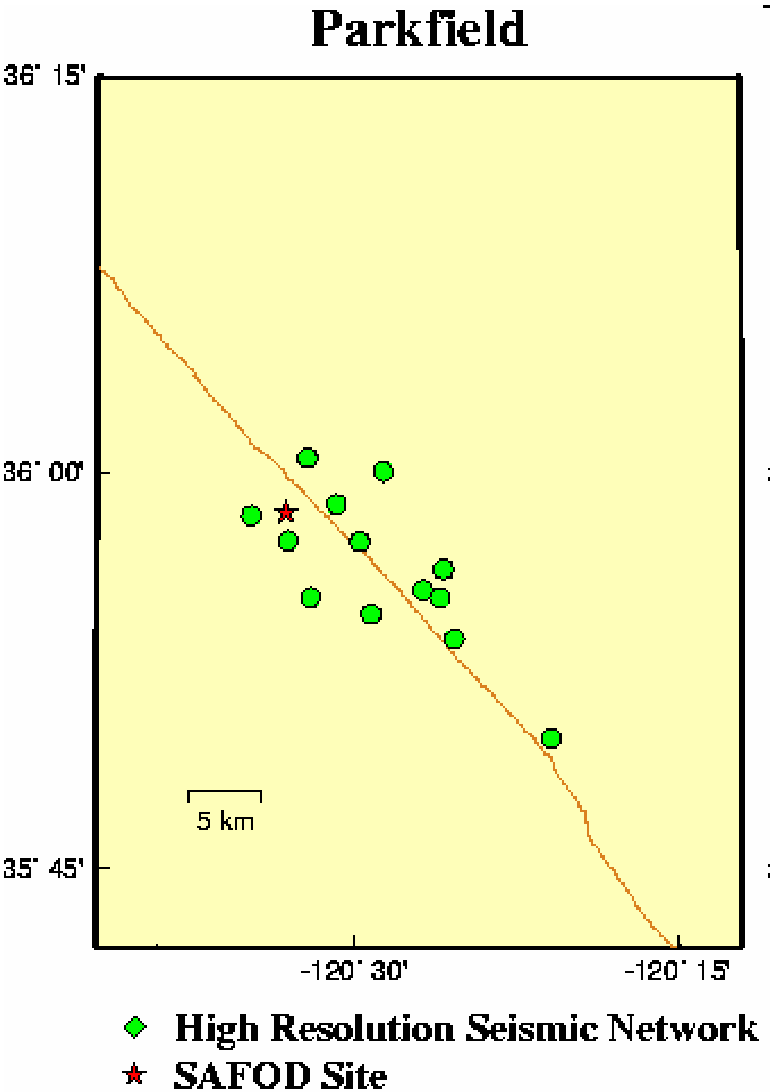
www.SanAndreasFault.org

Instrumentation in the Parkfield region



Parkfield High Resolution Seismic Network

- 13 borehole seismometers
- Operated by the Berkeley Seismological Laboratory
- Operational since 1987 with 10 stations, expanded to 13 in 2001



Unsworth et al. Internal structure of the San Andreas fault at Parkfield, California. Geology (1997) vol. 25 (4) pp. 359-362

- **Methods**: Magnetotelluric (MT) profile across fault
- Reflection seismic survey
- **Results**: flower structure of fractured material near surface, narrowing at depth
- Low resistivity fault core, suggesting presence of fluids

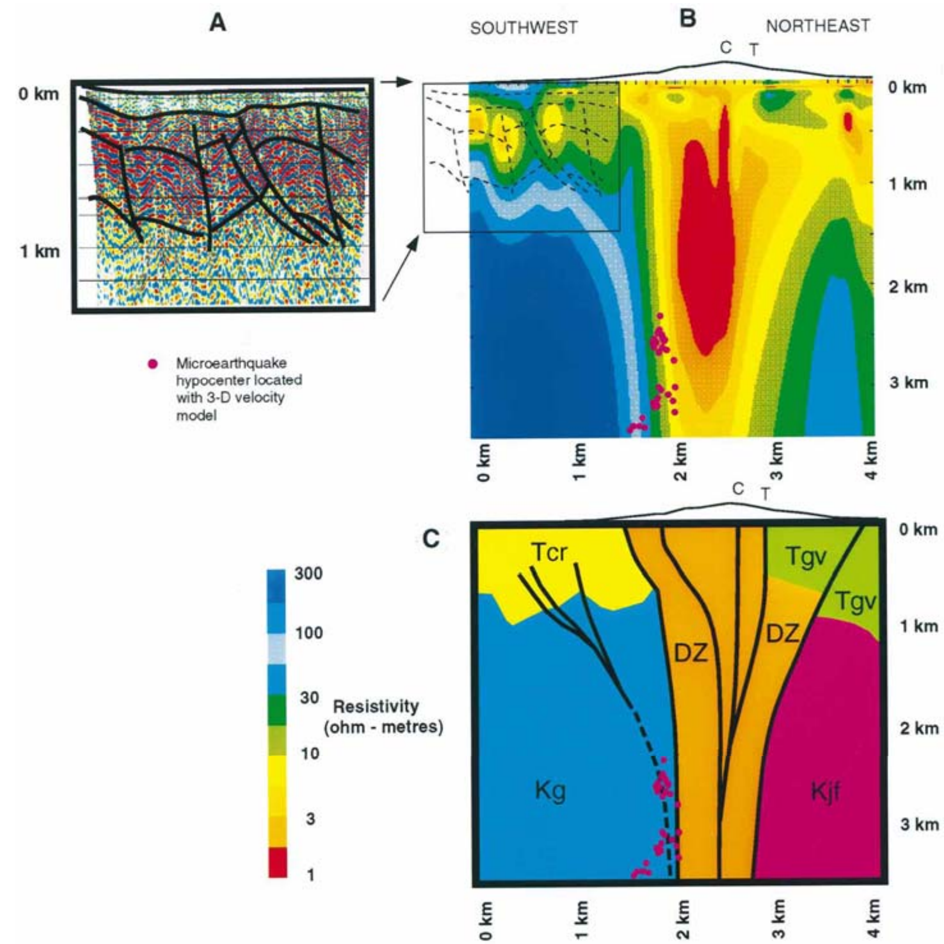
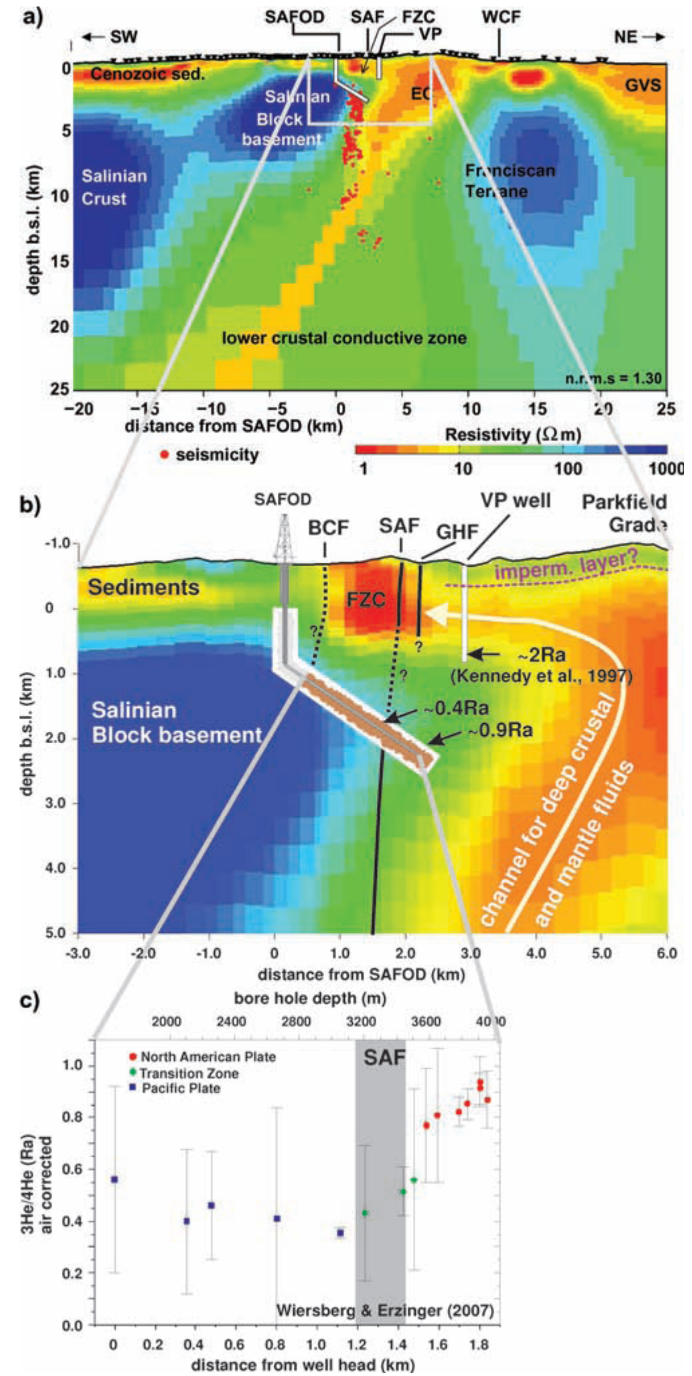


Figure 3. A: Migrated seismic reflection data on profile normal to fault. The depth of 1 km corresponds to a two-way travel time of 1 s. B: Electrical resistivity model that best fits observed magnetotelluric data presented in Figure 2. Location of active trace on basis of creep is denoted by T and topography shown on same vertical scale. C—crest of Middle Mountain. C: Schematic interpretation of the seismic and magnetotelluric data. Kg—Salinian granite, Tcr—Coast Range sedimentary units, Tgv—Tertiary Great Valley sequence, Kjf—Franciscan melange, and DZ—damaged zone.

Becken et al. A deep crustal fluid channel into the San Andreas Fault system near Parkfield, California. Geophysical Journal International (2008) vol. 173 (2) pp. 718-732

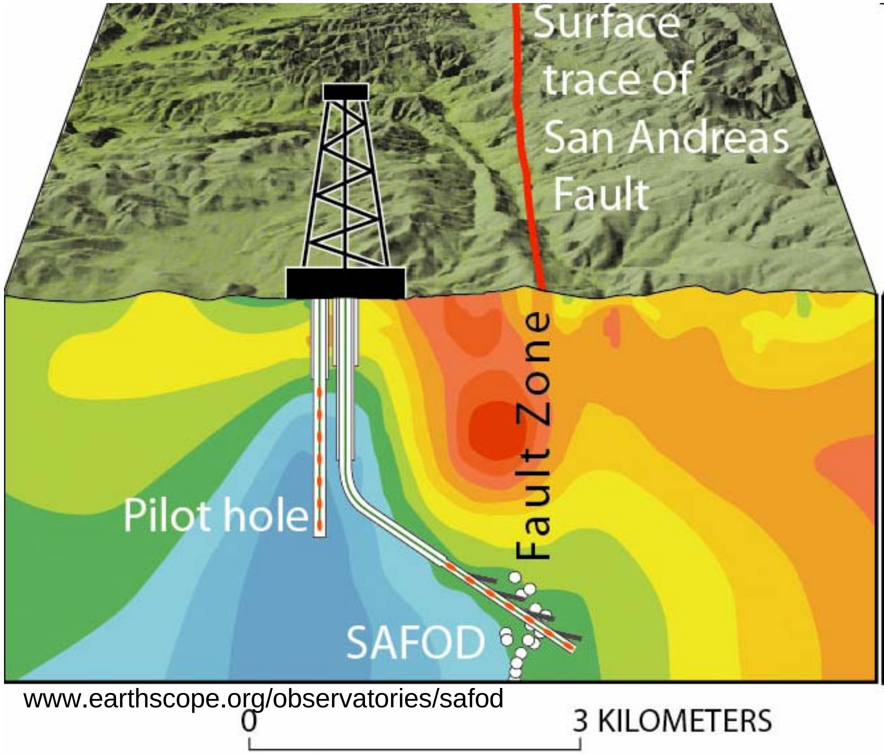
- **Methods**: Magnetotelluric (MT) profile across fault, analysis of $^{3}He/^{4}He$ ratios
- **Results**: conductive zone crossing fault at depth, extending to lower crust & possibly mantle
- Suggest deep mantle fluids originating W of fault, entering fault near surface from E



SAFOD

The San Andreas Fault Observatory at Depth

- 2.2 km pilot hole drilled and instrumented in 2002
- 3.2 km deep main hole drilled in 2007 into the fault zone
- Rock cores extracted directly from the fault
- Seismometer, tiltmeter, and accelerometer placed directly in fault zone at 3.2 km depth



www.earthscope.org/observatories/safod

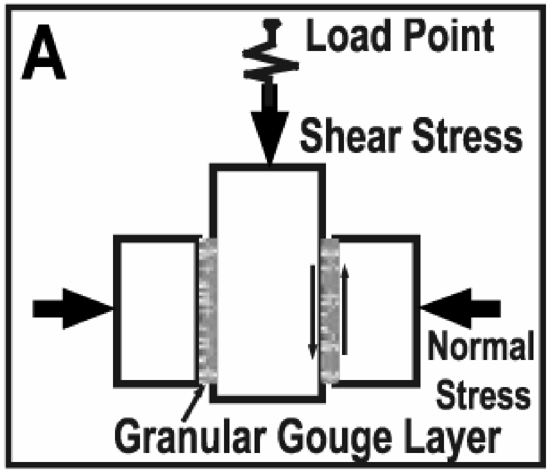
www.icdp-online.de/sites/sanandreas/news/news1.html

www.earthscope.org/es_doc/onsite/onsite_winter08.pdf

- 1-3 meters of fault gouge
- Serpentine layer and fragments

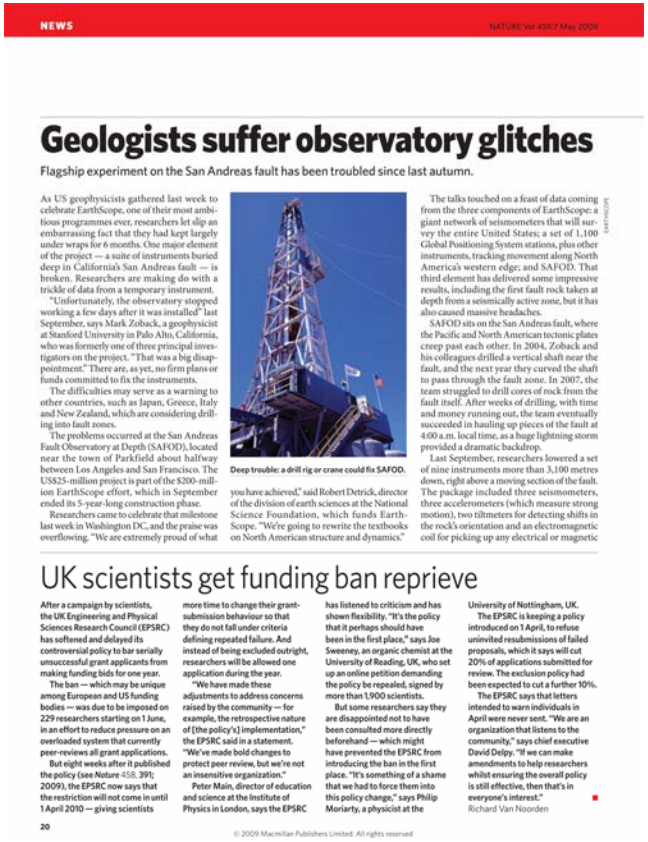
Carpenter et al. Frictional behavior of materials in the 3D SAFOD volume. Geophysical Research Letters (2009) vol. 36 (5) pp. L05302

- **Method**: apply shear stress to granular samples of various rocks to measure frictional coefficient
- Some samples from SAFOD drilling cuttings, some from elsewhere
- Frictional coefficient in fault is thought to be very low, from heat flow data
- **Results**: only large concentrations (>50%) of wet serpentinite or talc have low enough frictional coefficient



Seismometers in the Fault

- Seismometer, tiltmeter, and accelerometer placed directly in fault zone at 3.2 km depth
- Only worked for a few days, then all failed due to unknown causes
- A temporary seismometer was installed



NEWS NATURE|Vol 459|7 May 2009

Geologists suffer observatory glitches

Flagship experiment on the San Andreas fault has been troubled since last autumn.

As US geophysicists gathered last week to celebrate EarthScope, one of their most ambitious programmes ever, researchers let slip an embarrassing fact that they had kept largely under wraps for 6 months. One major element of the project — a suite of instruments buried deep in California's San Andreas fault — is broken. Researchers are making do with a trickle of data from a temporary instrument.

"Unfortunately, the observatory stopped working a few days after it was installed" last September, says Mark Zoback, a geophysicist at Stanford University in Palo Alto, California, who was formerly one of three principal investigators on the project. "That was a big disappointment." There are, as yet, no firm plans or funds committed to fix the instruments.

The difficulties may serve as a warning to other countries, such as Japan, Greece, Italy and New Zealand, which are considering drilling into fault zones.

The problems occurred at the San Andreas Fault Observatory at Depth (SAFOD), located near the town of Parkfield about halfway between Los Angeles and San Francisco. The US$25-million project is part of the $200-million EarthScope effort, which in September ended its 5-year-long construction phase.

Researchers came to celebrate that milestone last week in Washington DC, and the praise was overflowing. "We are extremely proud of what you have achieved," said Robert Detrick, director of the division of earth sciences at the National Science Foundation, which funds EarthScope. "We're going to rewrite the textbooks on North American structure and dynamics."

Deep trouble: a drill rig or crane could fix SAFOD.

The talks touched on a feast of data coming from the three components of EarthScope: a giant network of seismometers that will survey the entire United States; a set of 1,100 Global Positioning System stations, plus other instruments, tracking movement along North America's western edge; and SAFOD. That third element has delivered some impressive results, including the first fault rock taken at depth from a seismically active zone, but it has also caused massive headaches.

SAFOD sits on the San Andreas fault, where the Pacific and North American tectonic plates creep past each other. In 2004, Zoback and his colleagues drilled a vertical shaft near the fault, and the next year they curved the shaft to pass through the fault zone. In 2007, the team struggled to drill cores of rock from the fault itself. After weeks of drilling, with time and money running out, the team eventually succeeded in hauling up pieces of the fault at 4:00 a.m. local time, as a huge lightning storm provided a dramatic backdrop.

Last September, researchers lowered a set of nine instruments more than 3,100 metres down, right above a moving section of the fault. The package included three seismometers, three accelerometers (which measure strong motion), two tiltmeters for detecting shifts in the rock's orientation and an electromagnetic coil for picking up any electrical or magnetic

UK scientists get funding ban reprieve

After a campaign by scientists, the UK Engineering and Physical Sciences Research Council (EPSRC) has softened and delayed its controversial policy to bar serially unsuccessful grant applicants from making funding bids for one year.

The ban — which may be unique among European and US funding bodies — was due to be imposed on 229 researchers starting on 1 June, in an effort to reduce pressure on an overloaded system that currently peer-reviews all grant applications.

But eight weeks after it published the policy (see *Nature* 458, 391; 2009), the EPSRC now says that the restriction will not come in until 1 April 2010 — giving scientists more time to change their grant-submission behaviour so that they do not fall under criteria defining repeated failure. And instead of being excluded outright, researchers will be allowed one application during the year.

"We have made these adjustments to address concerns raised by the community — for example, the retrospective nature of [the policy's] implementation," the EPSRC said in a statement. "We've made bold changes to protect peer review, but we're not an insensitive organization."

Peter Main, director of education and science at the Institute of Physics in London, says the EPSRC has listened to criticism and has shown flexibility. "It's the policy that it perhaps should have been in the first place," says Joe Sweeney, an organic chemist at the University of Reading, UK, who set up an online petition demanding the policy be repealed, signed by more than 1,900 scientists.

But some researchers say they are disappointed not to have been consulted more directly beforehand — which might have prevented the EPSRC from introducing the ban in the first place. "It's something of a shame that we had to force them into this policy change," says Philip Moriarty, a physicist at the University of Nottingham, UK.

The EPSRC is keeping a policy introduced on 1 April, to refuse uninvited resubmissions of failed proposals, which it says will cut 20% of applications submitted for review. The exclusion policy had been expected to cut a further 10%.

The EPSRC says that letters intended to warn individuals in April were never sent. "We are an organization that listens to the community," says chief executive David Delpy. "If we can make amendments to help researchers whilst ensuring the overall policy is still effective, then that's in everyone's interest."

Richard Van Noorden

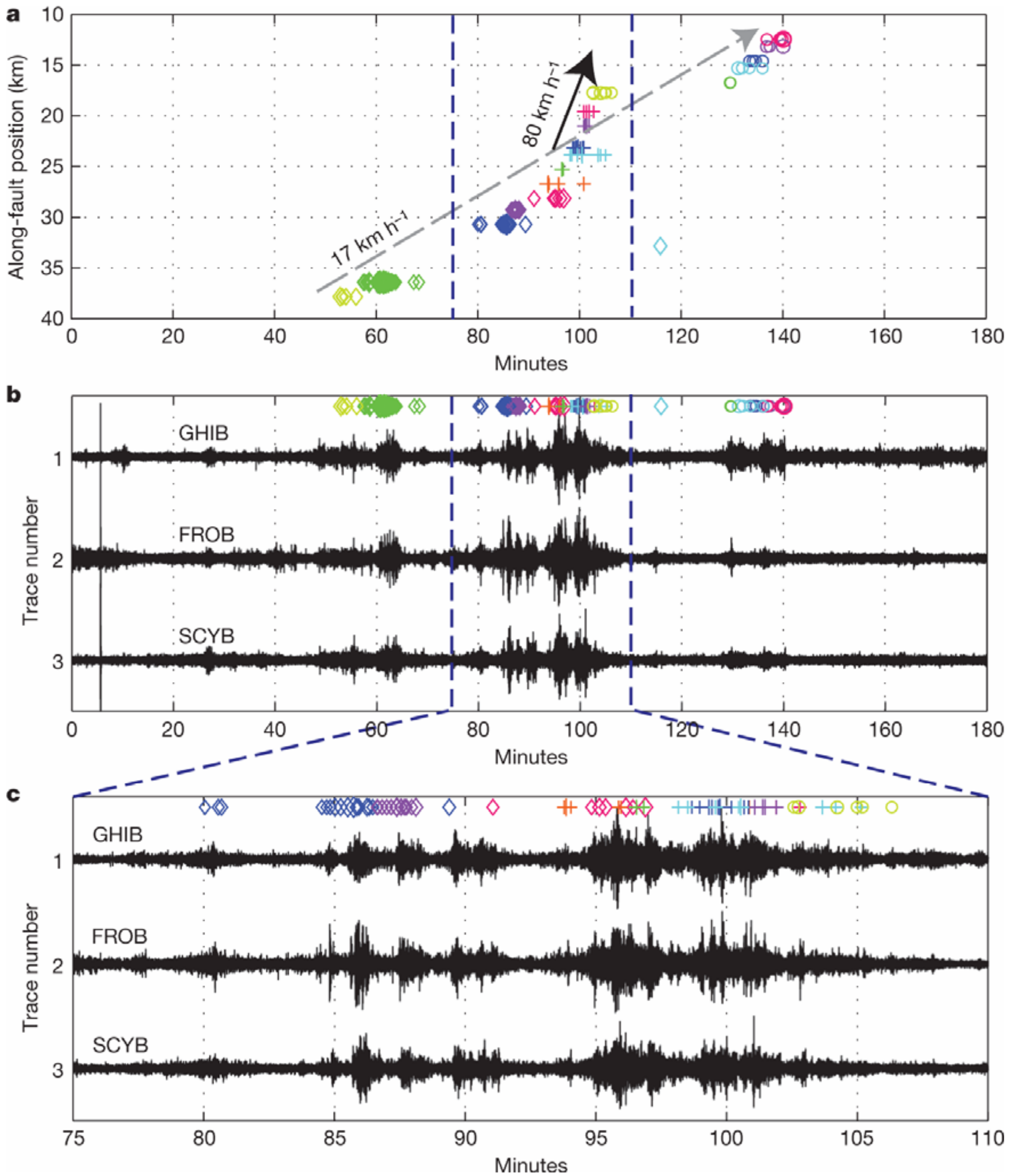
20

© 2009 Macmillan Publishers Limited. All rights reserved

Tremor

- Low-frequency (2-8 hz) recurring event, difficult to separate from noise. Multiple stations required for detection
- Found in subduction zones (Cascadia and Japan)
- Also observed on San Andreas Fault

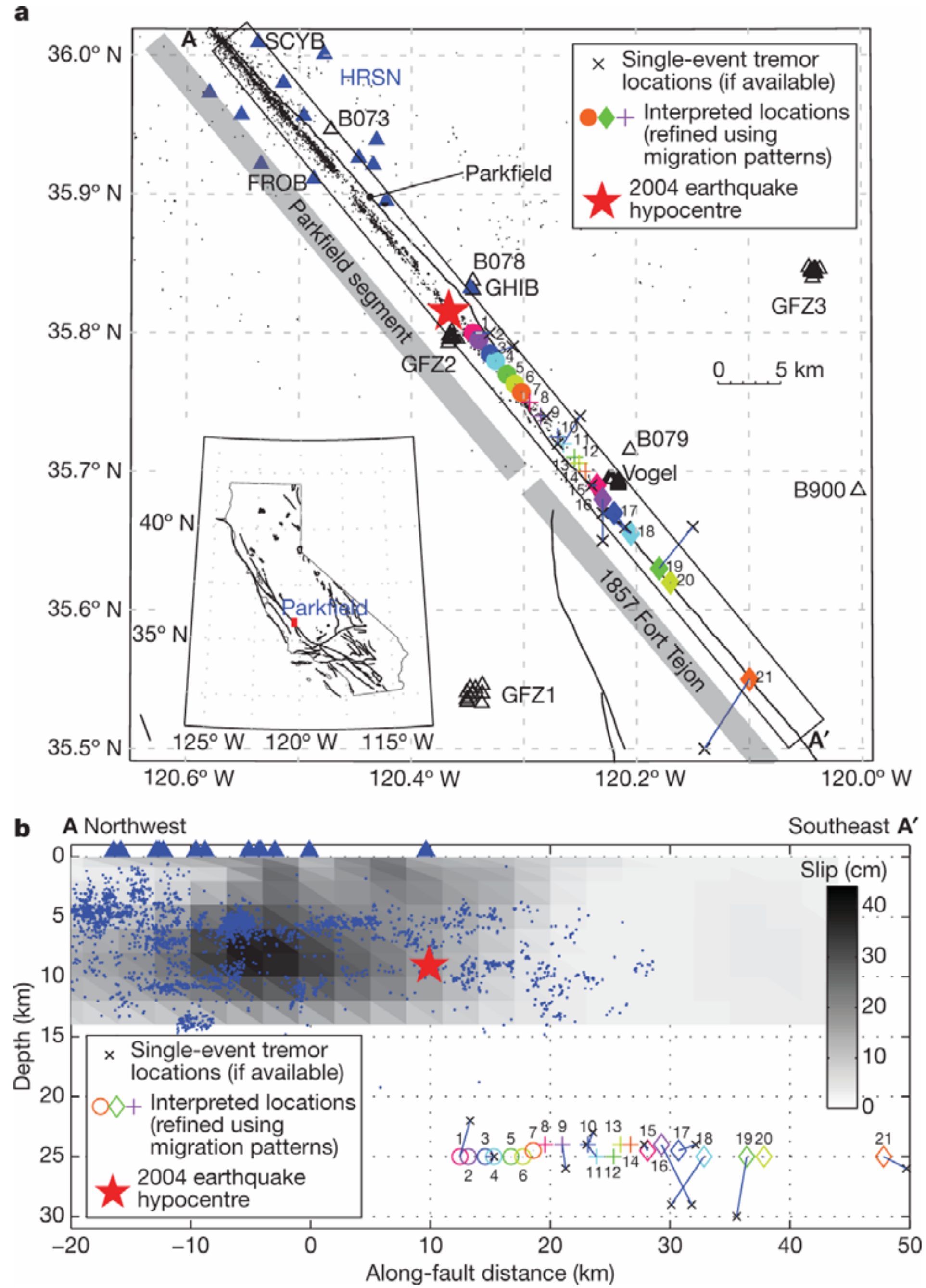
Shelly. Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas fault. Nature (2010) vol. 463 (7281) pp. 648-652



- **Methods**: choose 3-component waveform templates
- Cross-correlate templates with data stream to detect and time events
- Event "families" identified as similar waveforms across multiple stations

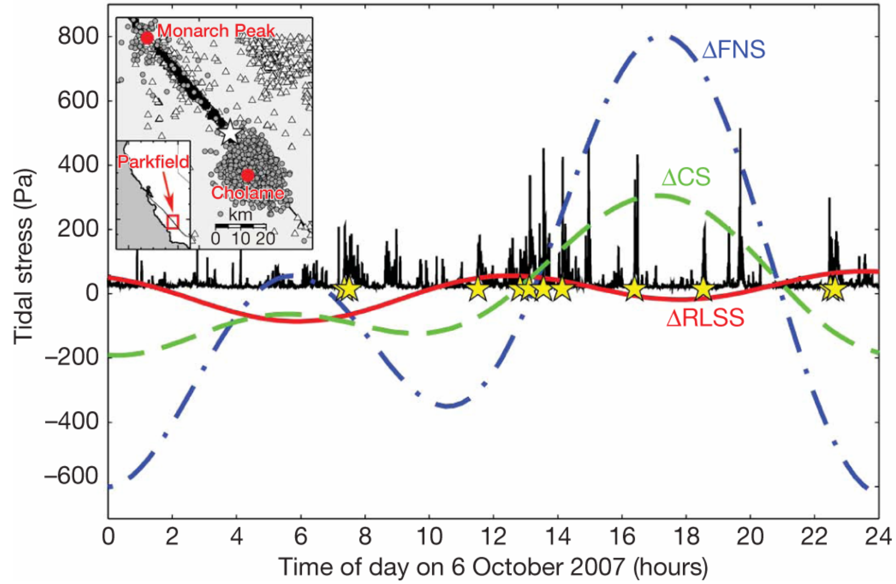
Shelly. Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas fault. Nature (2010) vol. 463 (7281) pp. 648-652

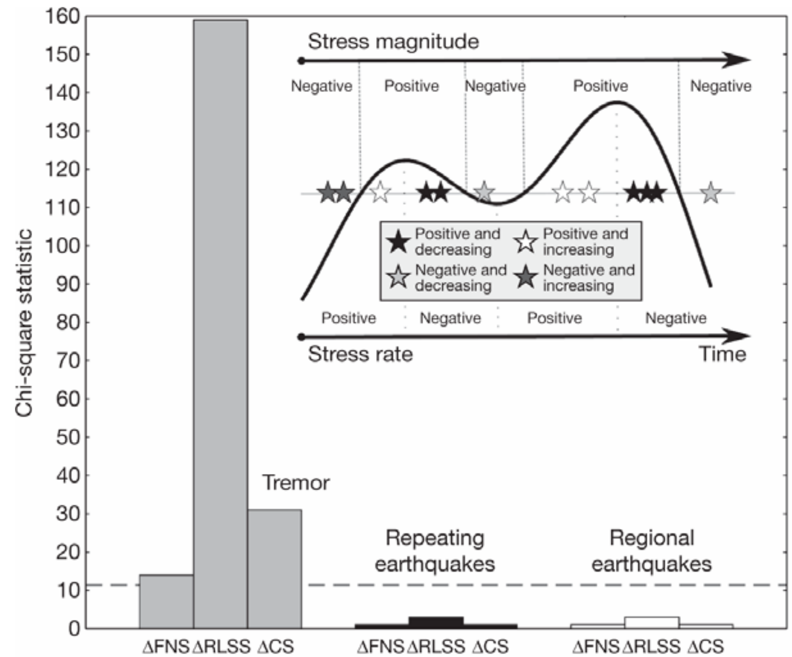
- **Results**: tremor migrates to NW along fault
- Migration rate varies widely, 15-80 km/hr
- Propagation can be >20 km along fault
- Seismicity depth 0-15 km
- Tremor depth ~25 km
- 15-25 km unknown ??
- Event frequency increased temporarily after Parkfield 2004 earthquake



Thomas et al. Tremor-tide correlations and near-lithostatic pore pressure on the deep San Andreas fault. Nature (2009) vol. 462 (7276) pp. 1048-1051

- **Methods**: calculate tidal shear, normal, and Coulomb stresses
- Correlate with occurrence of tremor
- **Results**: strong correlation of tremor with right-lateral shear stress (along fault)
- No correlation of earthquakes with RLSS





Key Points

- At Parkfield CA, fault at 3km depth consists of 1-3m of fault gouge, serpentinite
- Fault has low friction and low resistivity, probably due to wet serpentinite
- Earthquakes occur in upper 15 km of crust
- Tremor occurs near base of crust, ~25km depth
- Tremor is influenced by Earth tides, and generally migrates NW along fault
- Earthquakes are not influenced by tides