Large Earthquakes in Plate Interiors: A Challenge to Plate Tectonics

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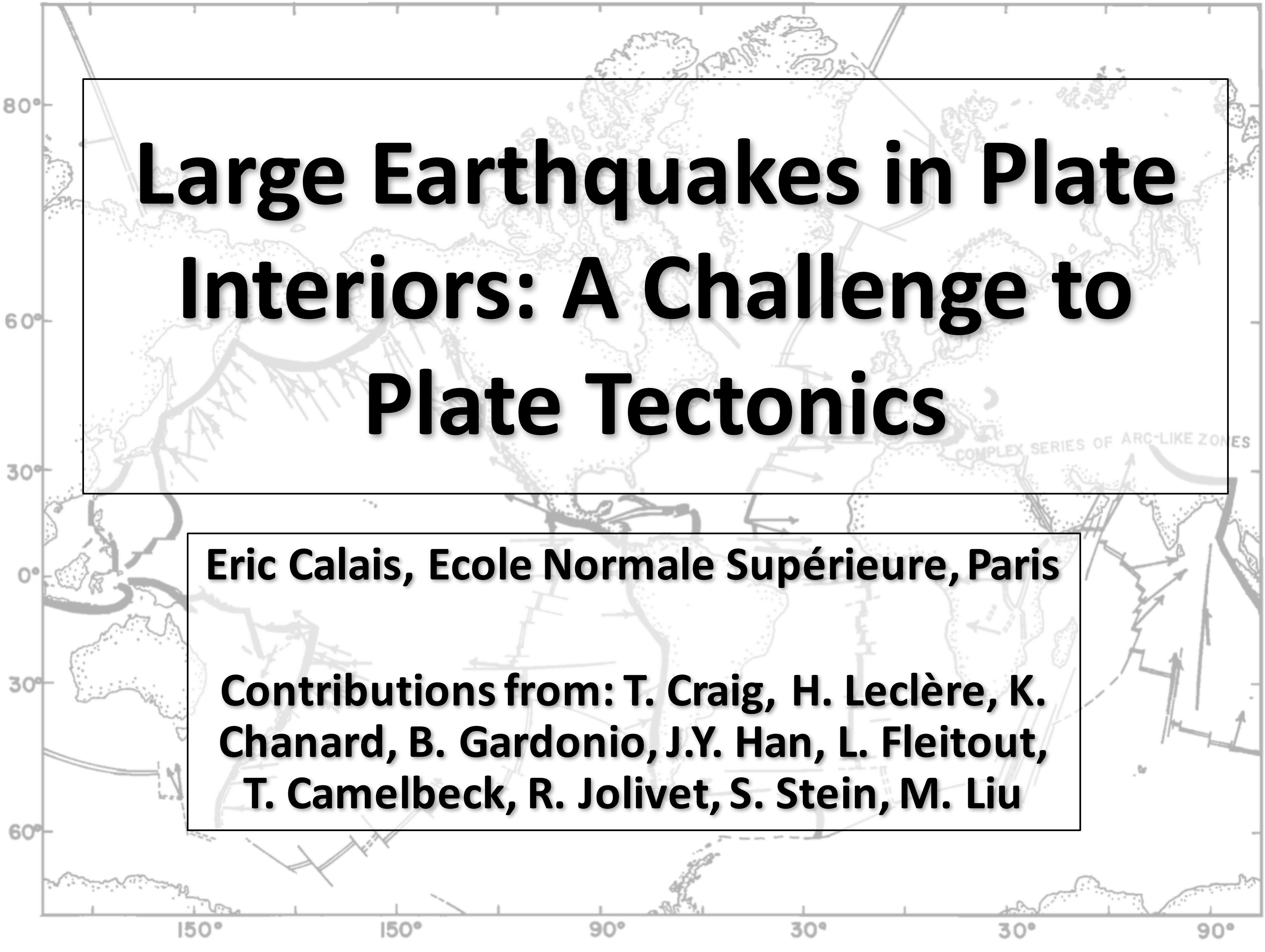
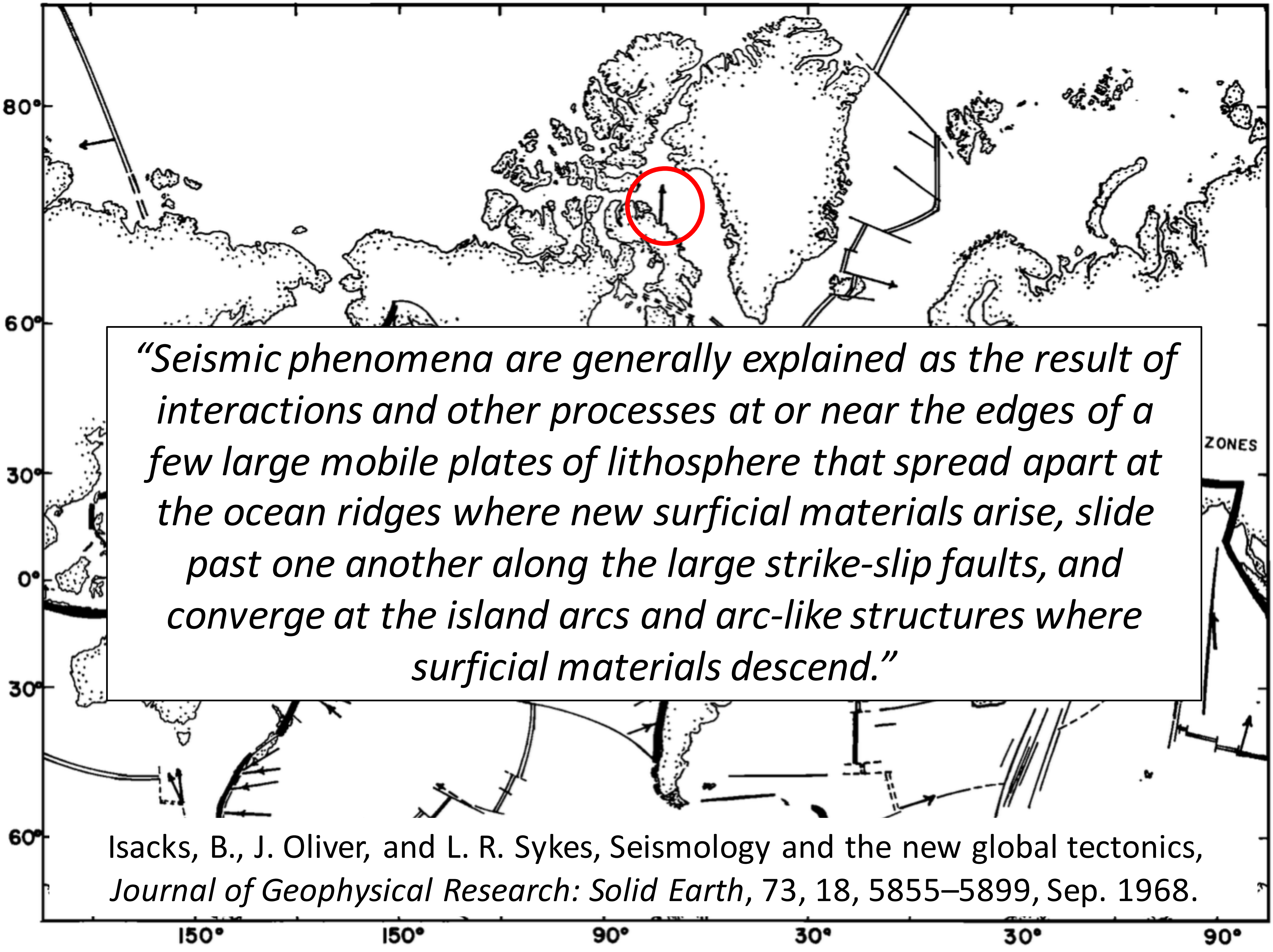
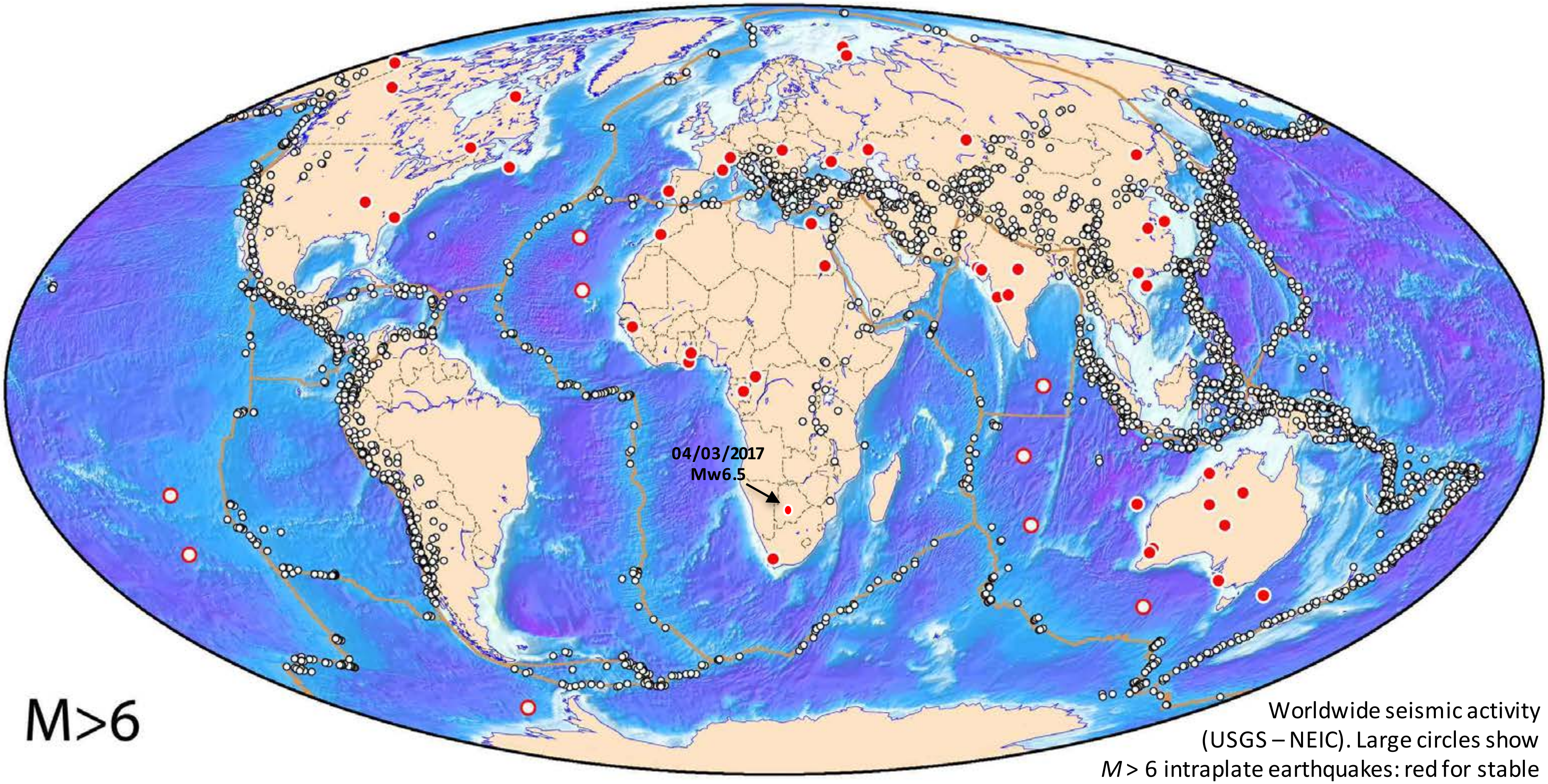




"Seismic phenomena are generally explained as the result of interactions and other processes at or near the edges of a few large mobile plates of lithosphere that spread apart at the ocean ridges where new surficial materials arise, slide past one another along the large strike-slip faults, and converge at the island arcs and arc-like structures where surficial materials descend."

Isacks, B., J. Oliver, and L. R. Sykes, Seismology and the new global tectonics, *Journal of Geophysical Research: Solid Earth*, 73, 18, 5855–5899, Sep. 1968.



Worldwide seismic activity (USGS – NEIC). Large circles show *M* > 6 intraplate earthquakes: red for stable continental regions, white for stable oceanic regions.

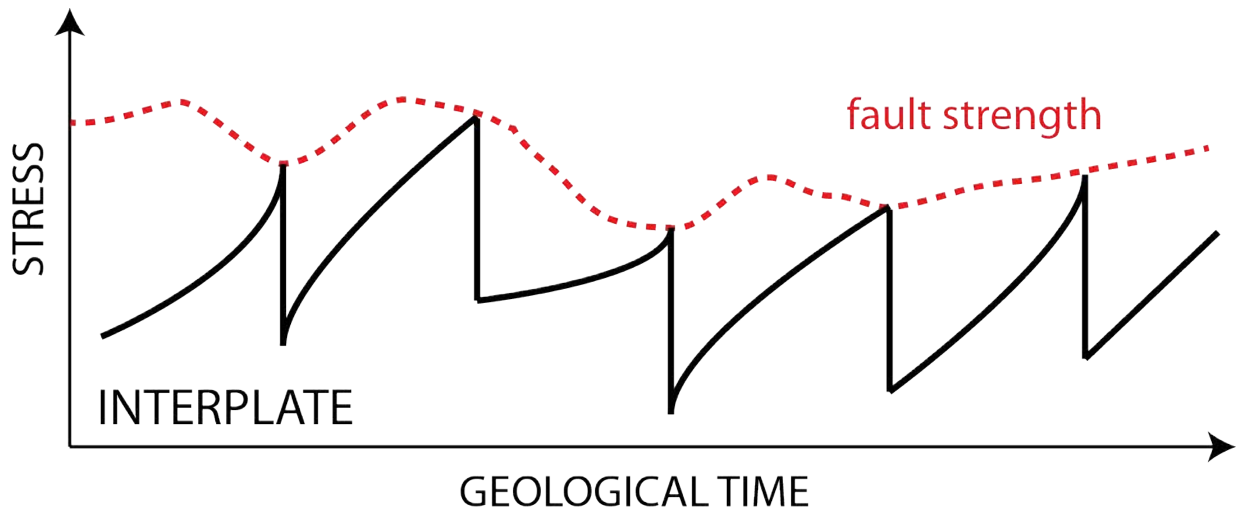
Stable continental regions (SCRs): “areas where the continental crust is largely unaffected by currently active plate boundary processes” (Johnston, 1989)

SCR seismicity is widespread – temporal and spatial logic unclear => a major challenge to our understanding: how do they relate to plate tectonics?

Impact on hazard assessment is significant.

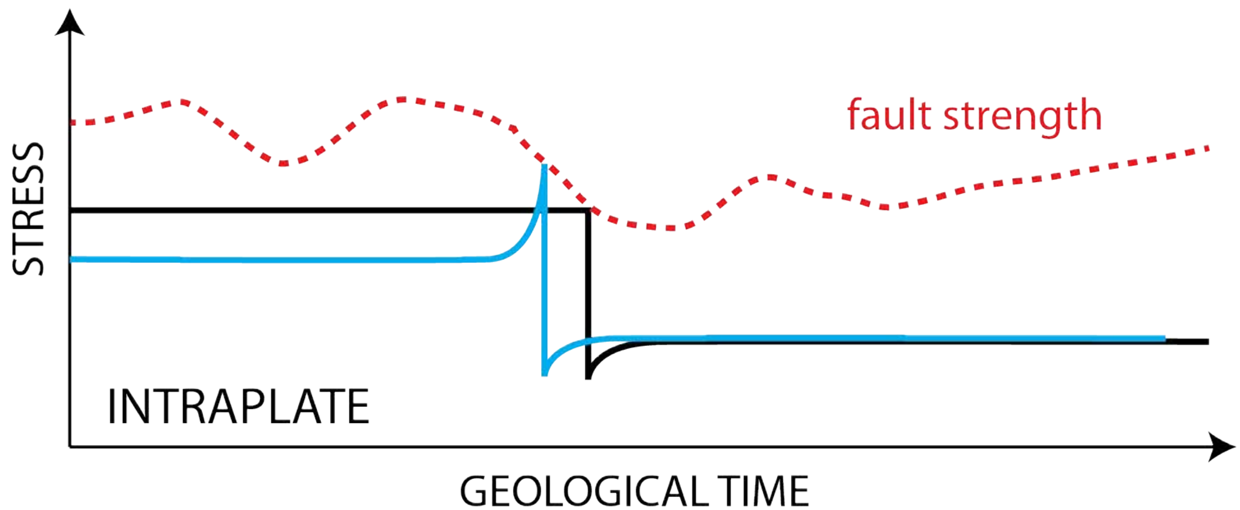
Earthquakes result from the localized accrual of tectonic stress at long-lived, plate boundary active faults in a steady-sate system where a balance is achieved between the rates at which strain accrues and is released on faults.

SCR faults = very, very, very, very slow faults?

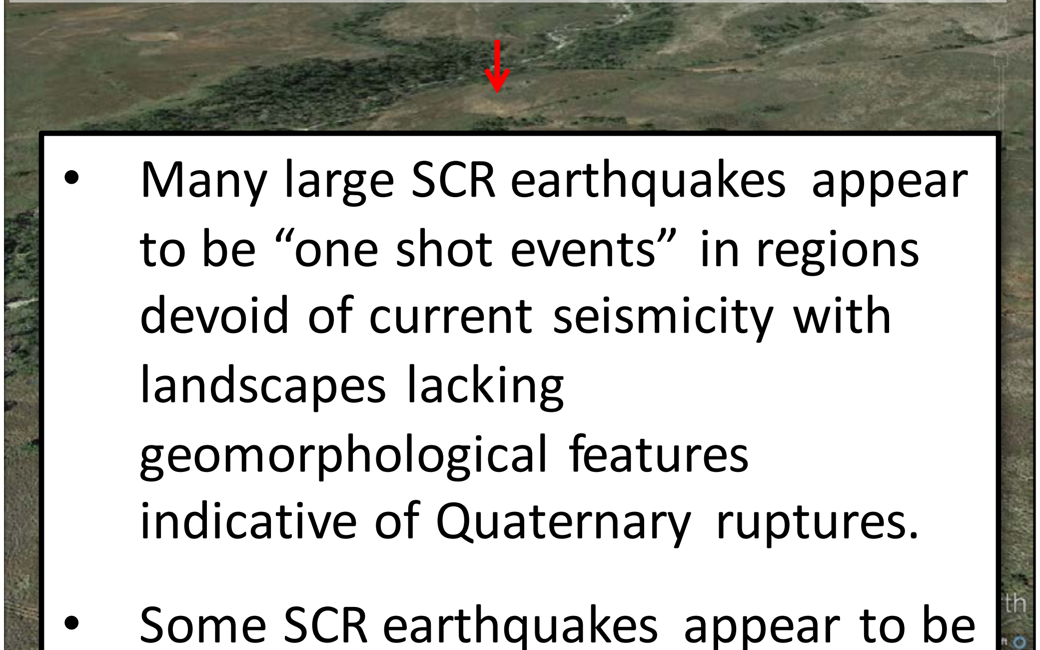


"Earthquakes occur as a result of global plate motion"
(Kanamori and Brodsky, Rep. Prog. Phys., 2004)

While long-term tectonic stress provides the energy that is released during large SCR earthquakes, they are triggered by transient perturbations of local stress that release elastic energy from a pre-stressed crust where faults are at failure equilibrium.

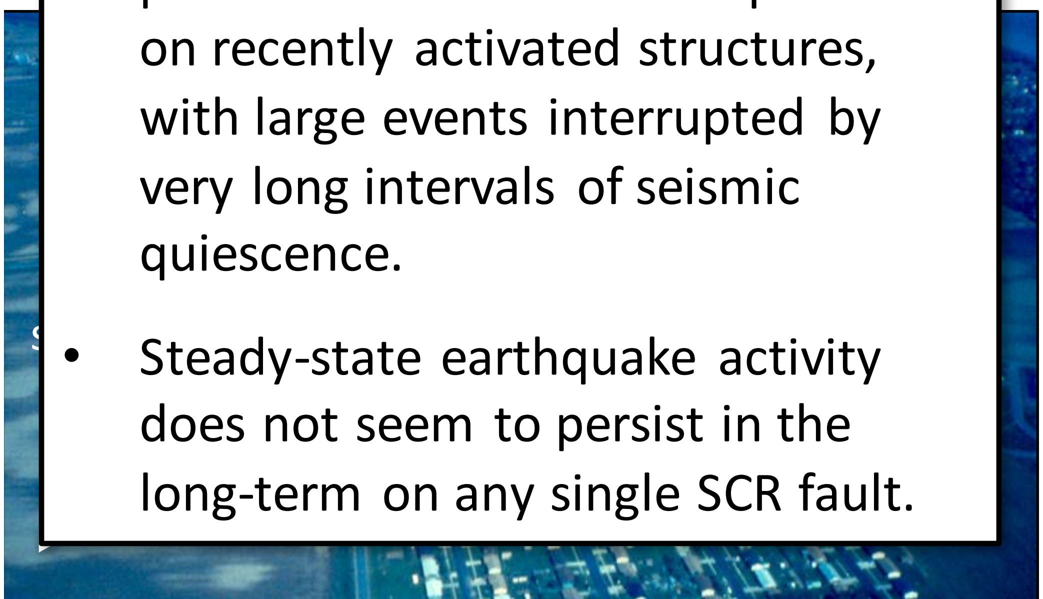


SCR earthquakes occur as a result of transient stress/strength perturbations and release elastic energy from a pre-stressed crust.

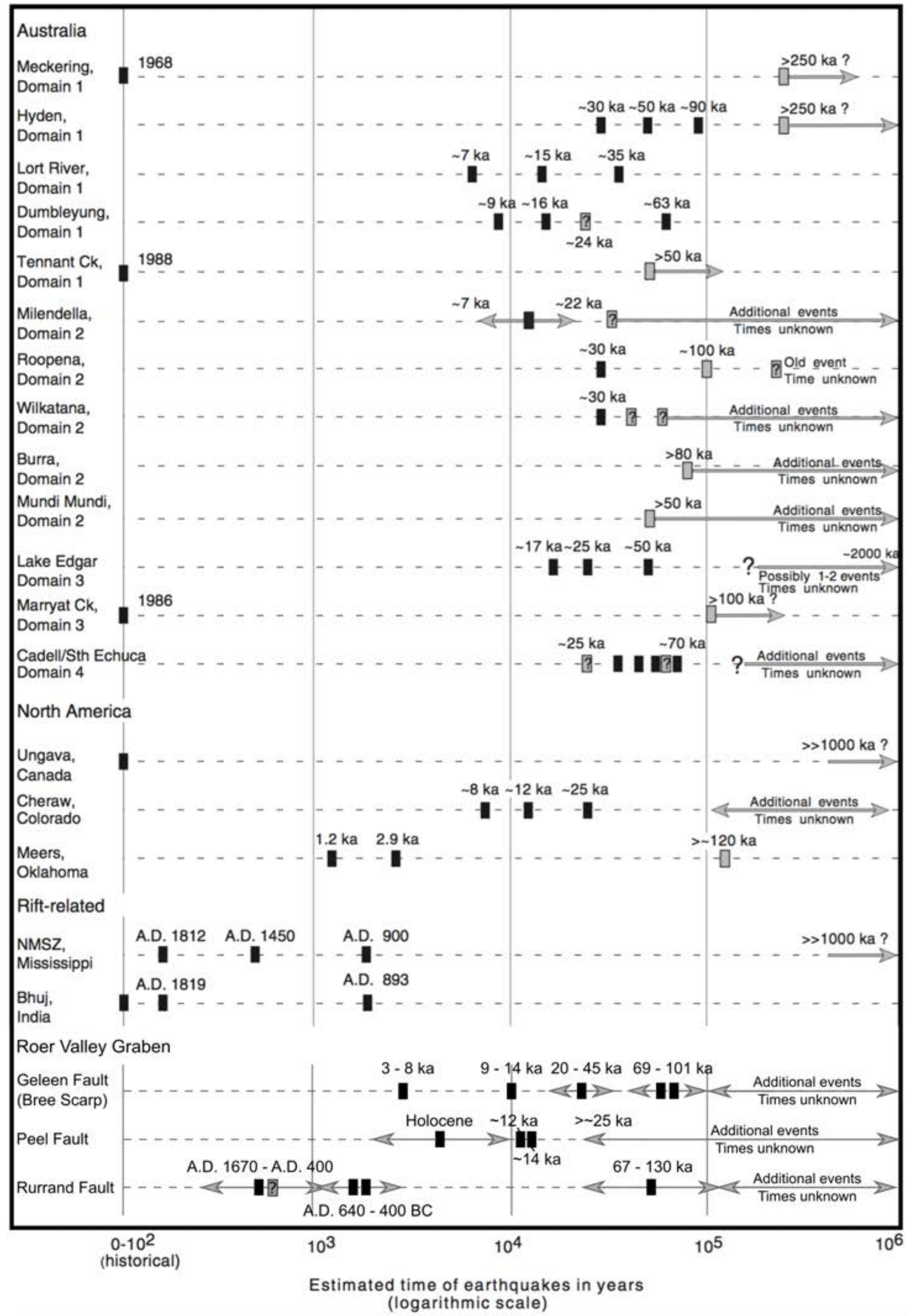


Meers fault, Oklahoma: last surface faulting 1200-2900 yrs ago, nothing in the previous 100,000 yrs, no current seismicity.

- Many large SCR earthquakes appear to be “one shot events” in regions devoid of current seismicity with landscapes lacking geomorphological features indicative of Quaternary ruptures.
- Some SCR earthquakes appear to be part of millennial-scale sequences on recently activated structures, with large events interrupted by very long intervals of seismic quiescence.
- Steady-state earthquake activity does not seem to persist in the long-term on any single SCR fault.



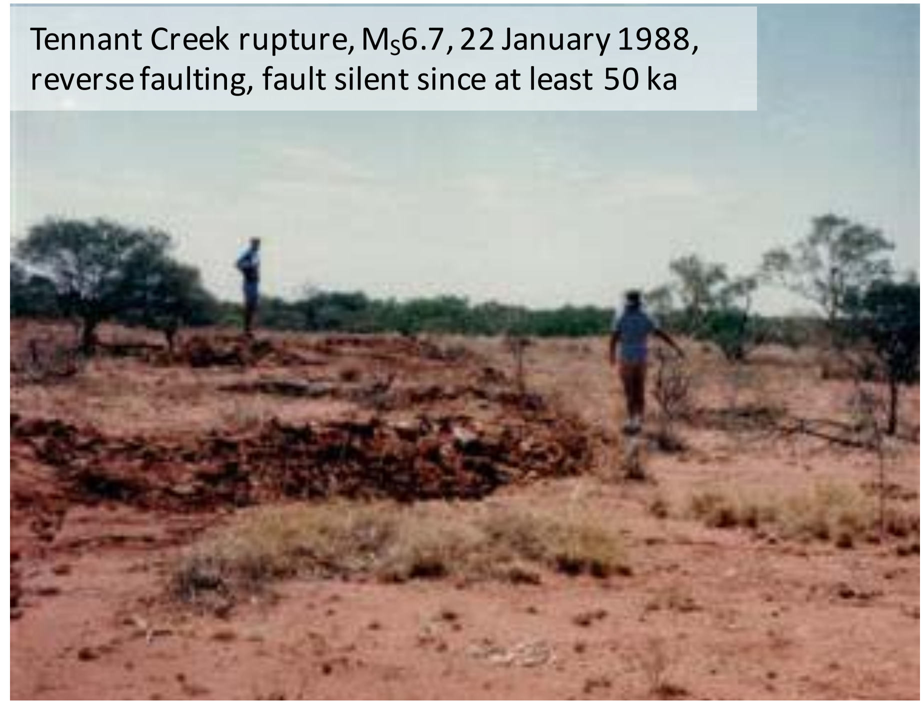
New Madrid, central U.S.: activated in the Holocene, 4 large regional events in the past 2,500 yrs



Single or clustered activity of most SCR faults does not represent their long-term behavior, during which the faults are mostly inactive.

- These short time intervals of seismicity indicate short-term stress or fault strength variations: argues against SCR earthquakes being triggered by tectonic stresses, which change slowly on timescales of millions of years.

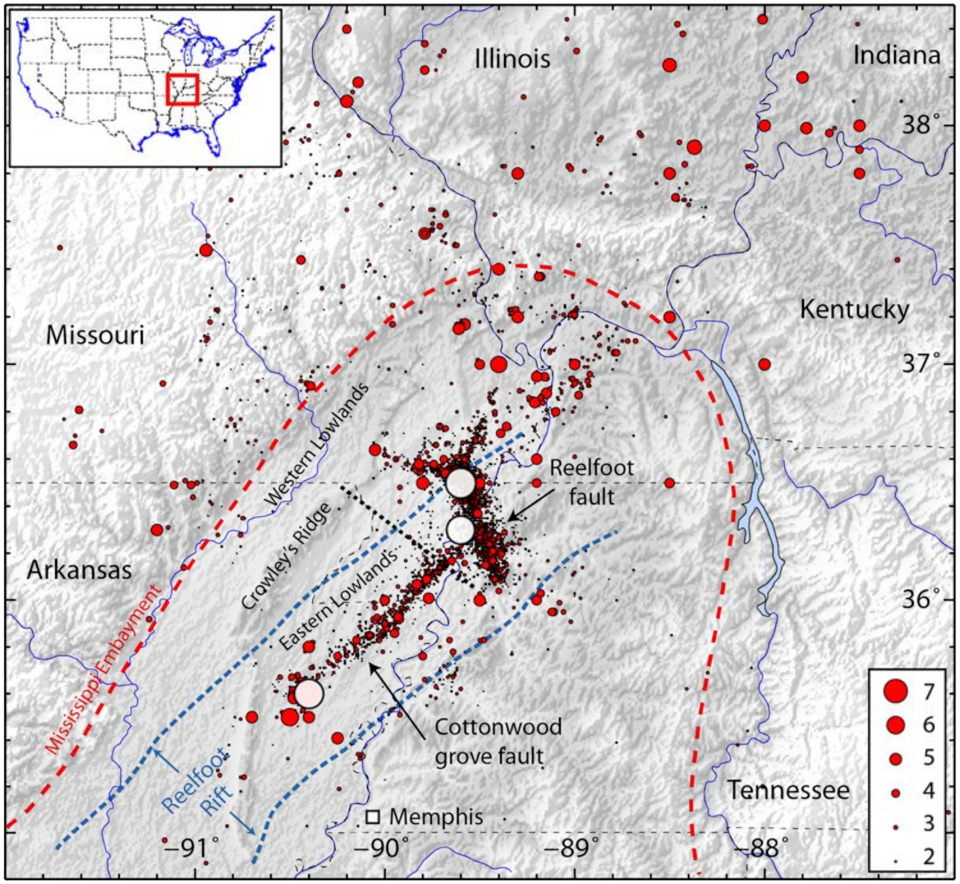
- SCR faults are likely not loaded individually at a constant rate, in contrast to plate boundary faults. This argues against interseismic strain localization on individual SCR fault zones.

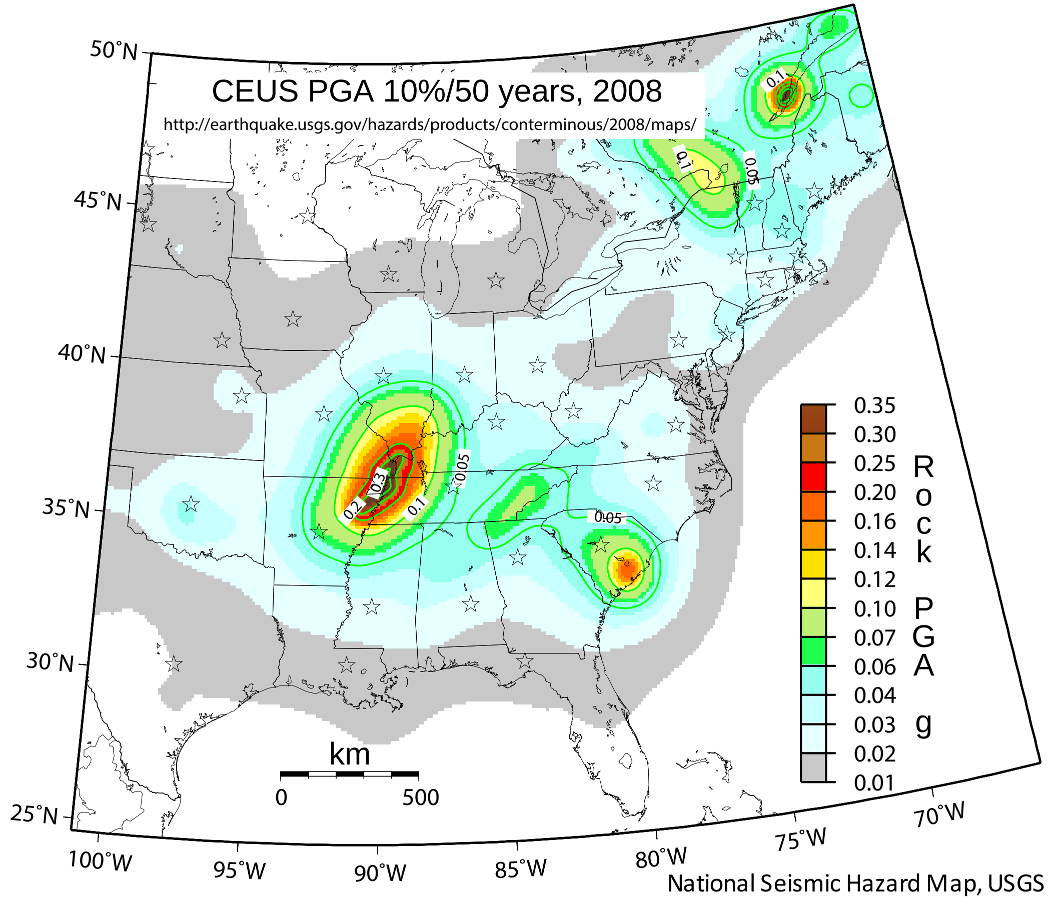


Tennant Creek rupture, M_S6.7, 22 January 1988, reverse faulting, fault silent since at least 50 ka

Hebron fault rupture, 40 km-long, single earthquake, Holocene, normal faulting

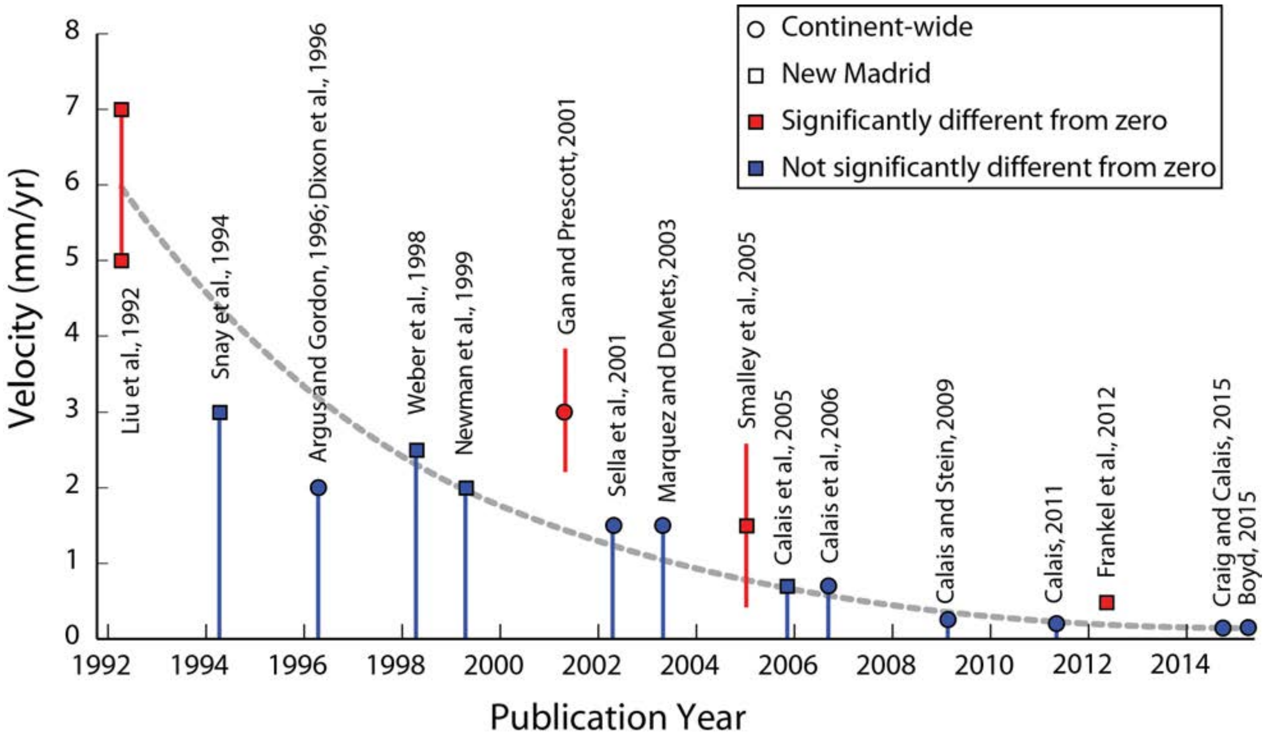
The New Madrid Earthquake Sequence





- 16 December 1811, M7.3, Cottonwood Grove fault
- 16 December 1811, M7.0, Cottonwood? Reelfoot?
- 23 January 1812, M7.0, S. Illinois?
- 7 February 1812, M7.5, SW-dipping Reelfoot thrust
- Current seismicity = aftershocks?

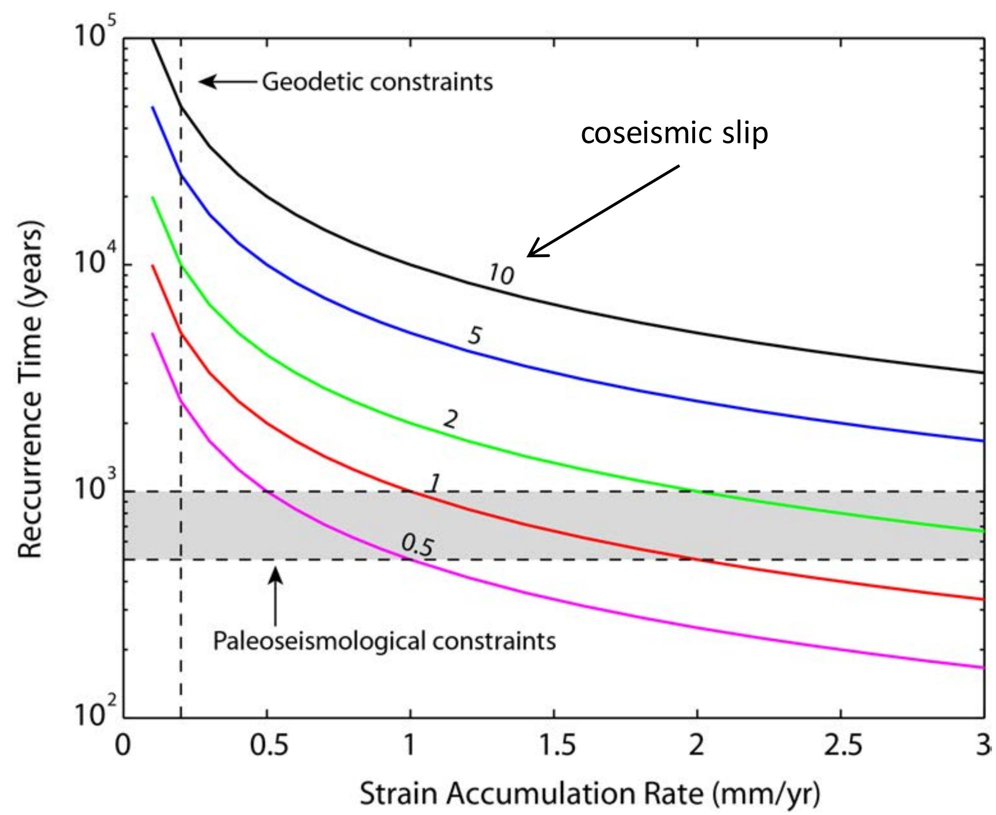
- PSHA => up to 0.3 g for 10%/50 years.
- The occurrence of similar earthquakes today could be catastrophic.
- Reducing vulnerability is costly.



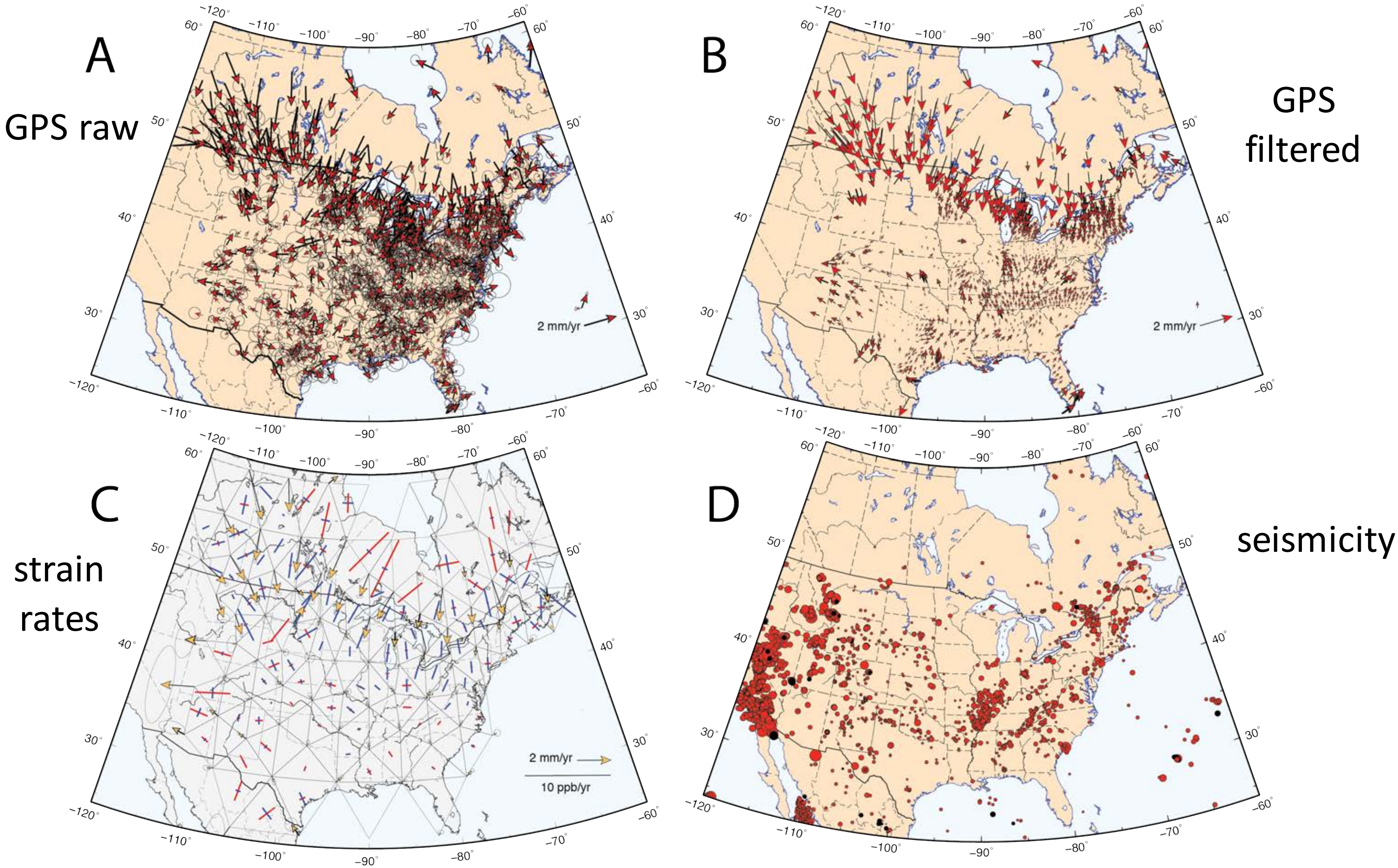
There is no evidence for present-day, localized strain accumulation in SCRs.

In the NMSZ, seismic strain release is ~ one order of magnitude larger than strain accumulation over past 5,000 yrs

- Not steady-state
- Releases "fossil" strain

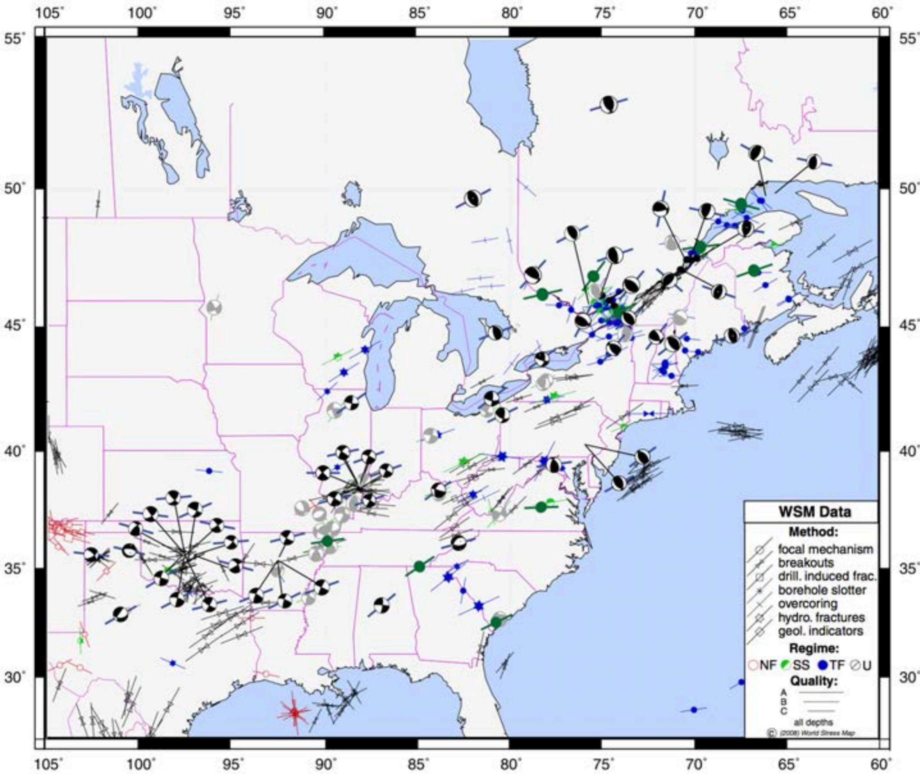


Craig and Calais, JGR, 2014

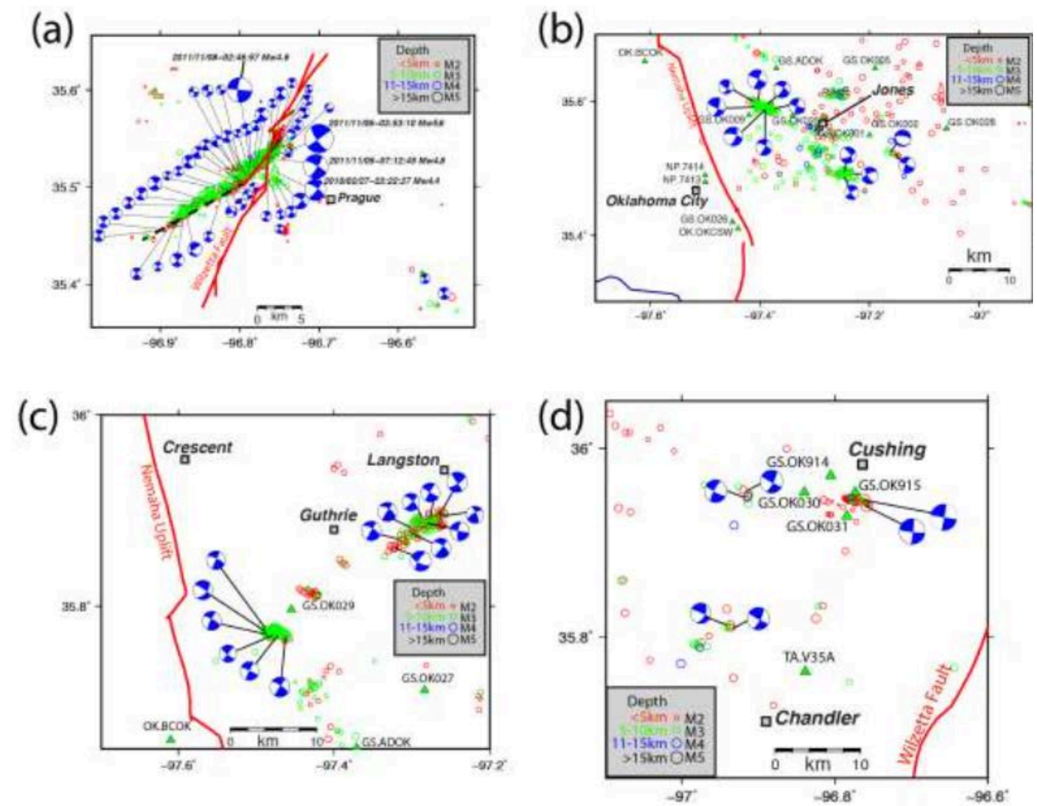


There is long wavelength horizontal deformation (Glacial Isostatic Adjustment) – it does not correlate with current seismicity => strain accumulation and release should be thought of as decoupled

Calais, Camelbeeck, Stein, Liu, and Craig, GRL, 2006

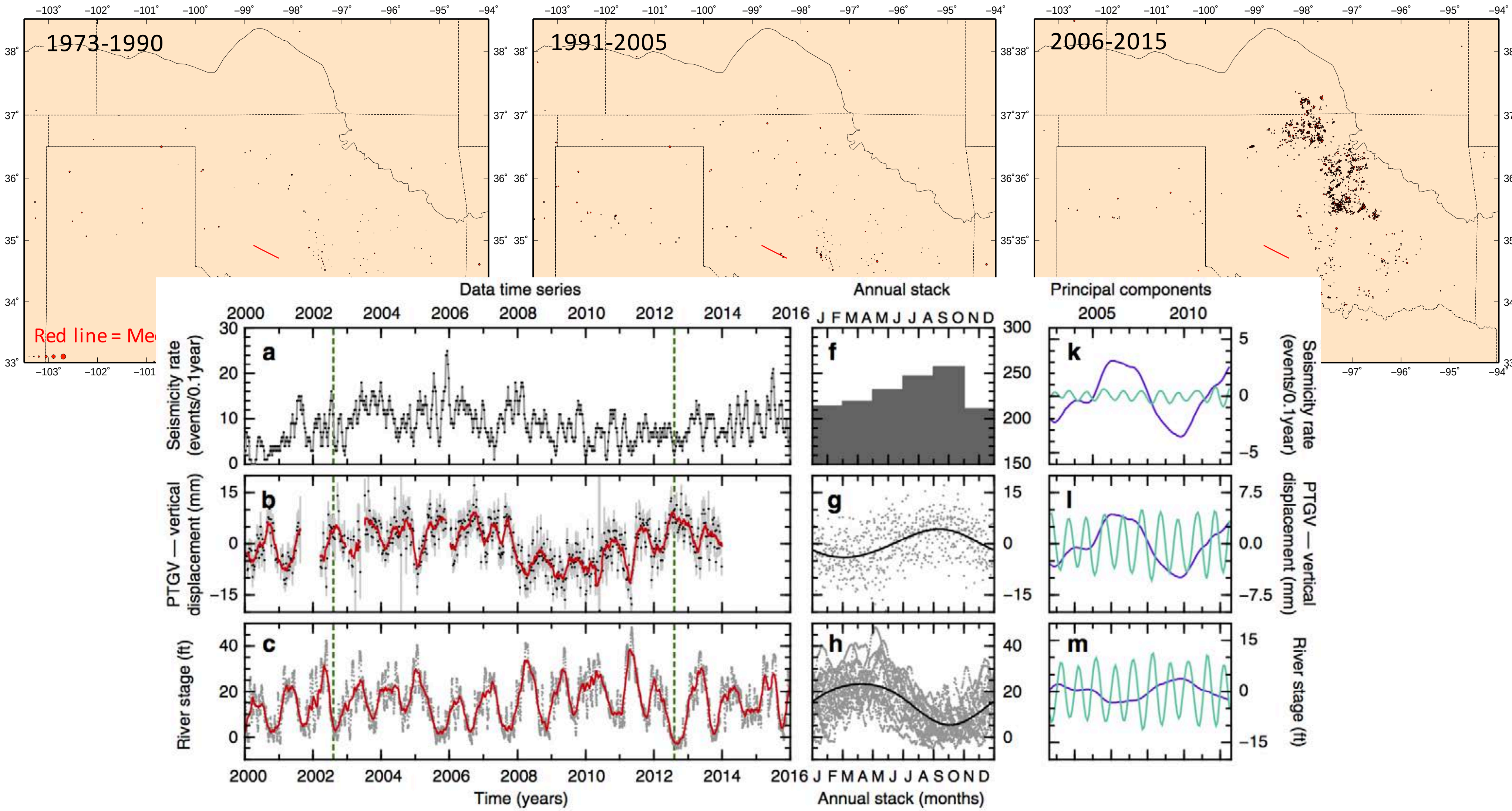


Hurd and Zoback, SRL 2012



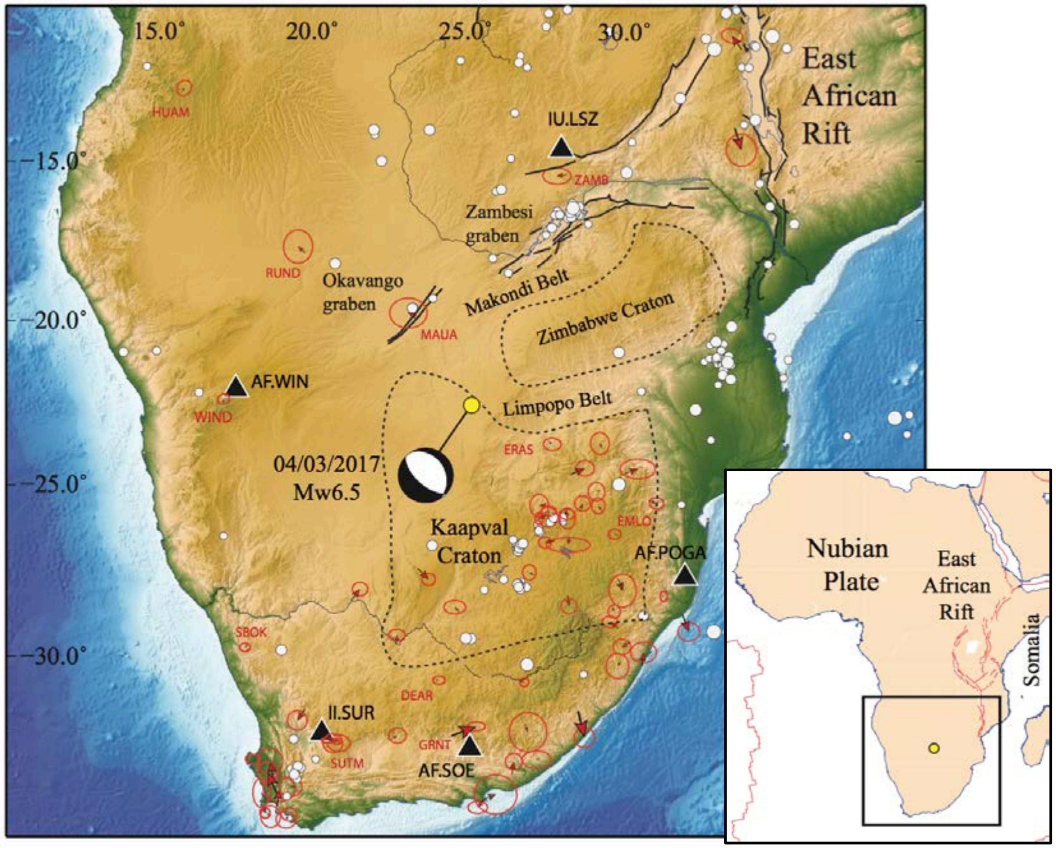
McNamara et al., GRL 2015

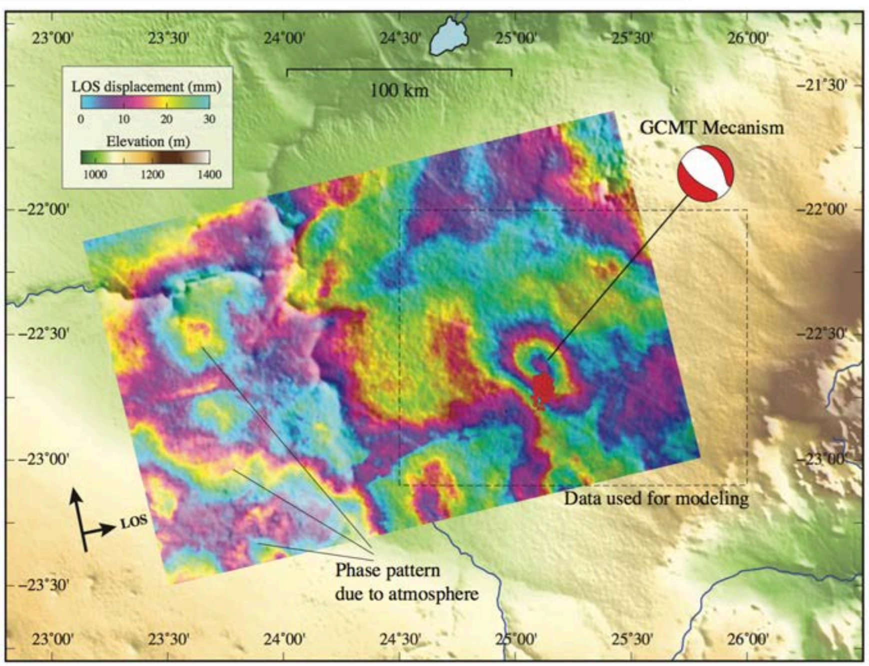
- Tectonic stress in SCR (a.k.a. ambient, or background, or static stress) <= lateral variations of gravitational potential energy (includes ridge-push) + tractions at base of plates + tractions along plate boundaries in the far field => vary slowly with distance – and very slowly with time.
- Crust breaks with mechanisms imposed by the static ambient stress field – these earthquakes release this static ambient stress.
- **Does this necessarily mean that this static ambient tectonic stress is responsible for bringing individual faults to failure?**

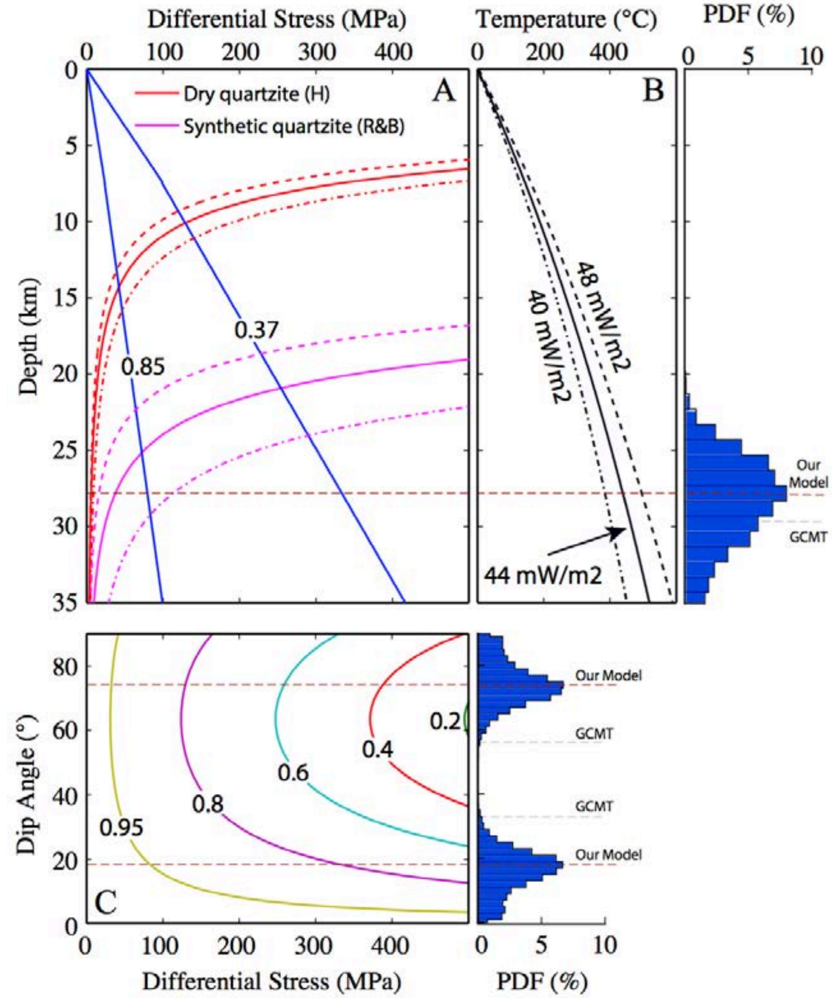


Seismicity in the NMSZ shows annual and pluri-annual modes that are common with hydrology (Craig, Chanard, and Calais, Nat. Com. 2017)

SCR earthquakes are easily triggered by small stress changes superimposed onto the background, static stress field.
SCR faults are at failure equilibrium in a pre-stressed crust able to sustain large differential stresses.



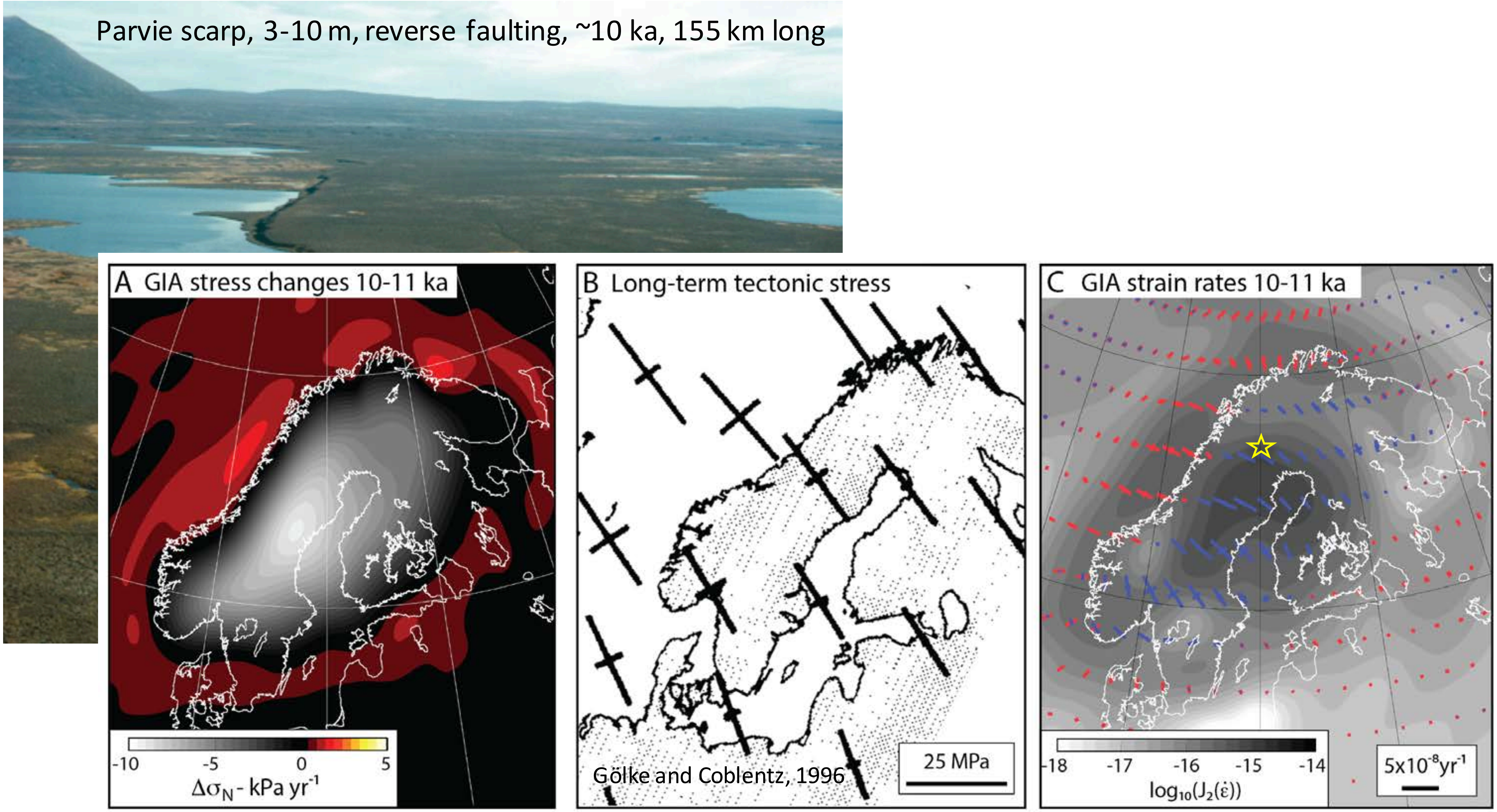




A lower-crust earthquake that can be explained by fluid overpressure.

Role of deep fluids in triggering SCR events?

(Gardonio, Jolivet, Calais, and Leclère, GRL, in press)



End-glacial faults did not release strain building up at the time

=> SCR crust stores elastic energy over time scales that are longer than observable by geodesy or paleoseismology

Craig, Calais, Fleitout, Bollinger, Scotti, GRL, 2017

Summary (testable hypotheses):

- SCR earthquakes do not persist on any single fault system.
- SCR faults do not localize stress or strain accrual.
- SCR faults are at failure equilibrium.
- SCR crust is a reservoir of “fossil strain” stored over long geological times as a result of slowly varying tectonic forces.
- SCR earthquakes are triggered by transient variations of local stress that modulate the slowly-varying, background tectonic stress.

Implications

Contrary to PBZs where faults are brought to failure by the localized accumulation of tectonic stresses, the triggering mechanism (transient stress changes) is not related to the strain accumulation mechanism (long-term, ambient tectonic stress).

Large SCR earthquakes:

- Locally release fossil strain stored in the bulk of the continental crust over long geological time – “delayed plate tectonics”
- Can occur in regions with no previous seismicity and no surface evidence for current strain accumulation.
- Need not repeat, since the tectonic loading rate is close to zero => concepts of recurrence time or fault slip rate do not apply.
- Present a hazard that is more distributed than usually thought.