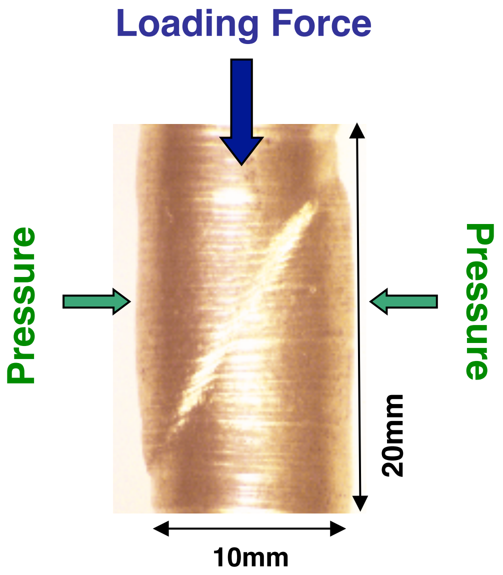
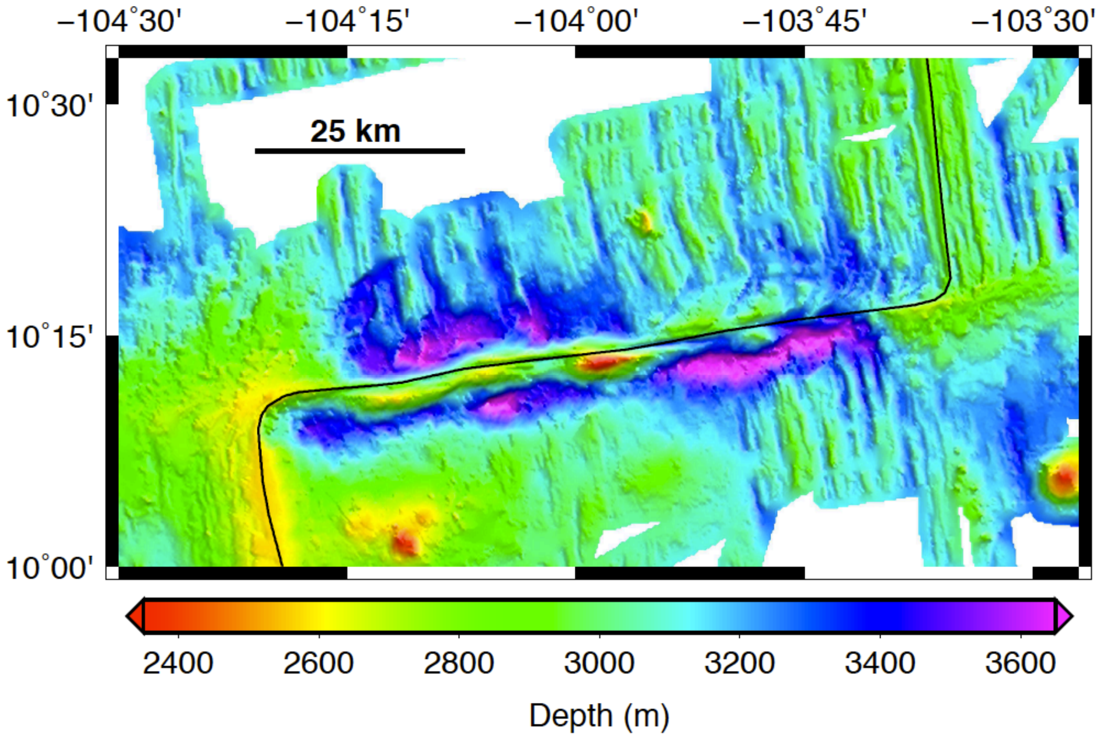
Understanding slip on oceanic transform faults through observations from the lab to the fault scale

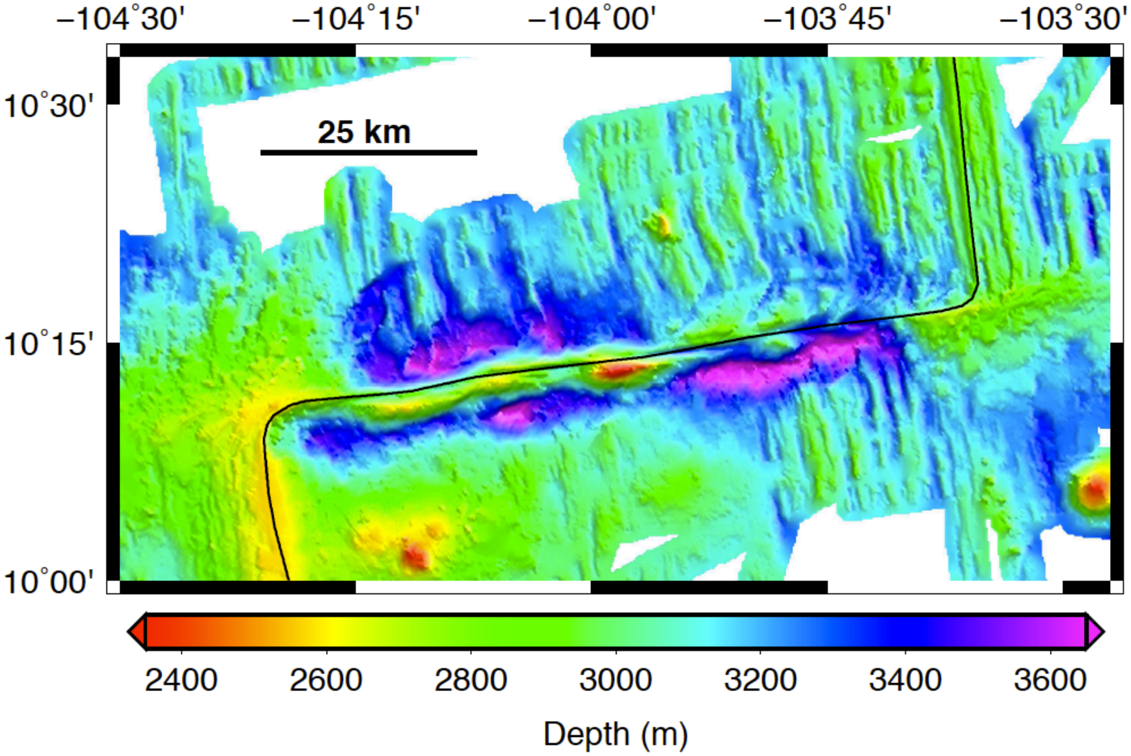


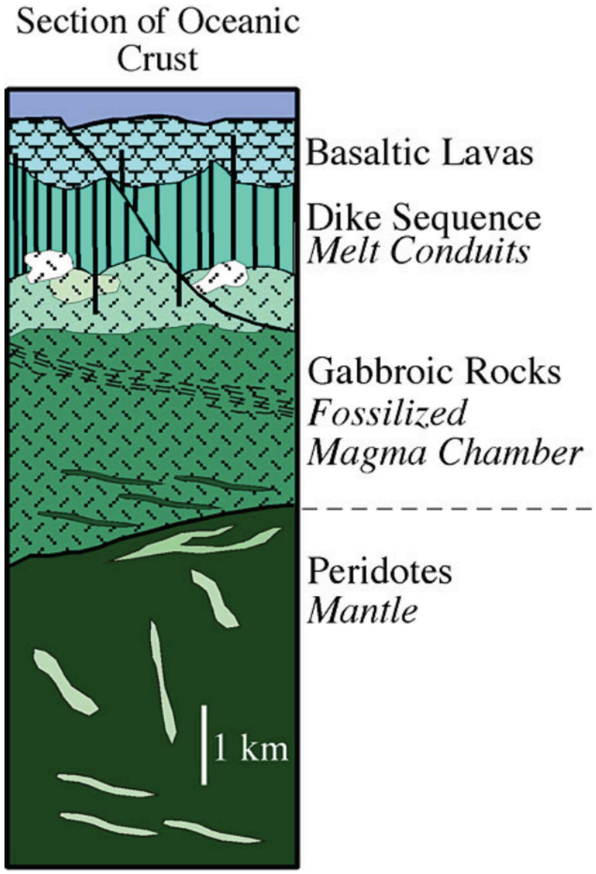


Margaret Boettcher, University of New Hampshire
CIG Workshop, Golden CO, June 2012

Oceanic Transform Faults are Relatively Simple

1. Simple Geometry (well defined length & slip rate)
2. Long-lived with large cumulative offsets
3. Simple Composition: Gabbro, Peridotite, and alteration phases (e.g. serpentine and talc)





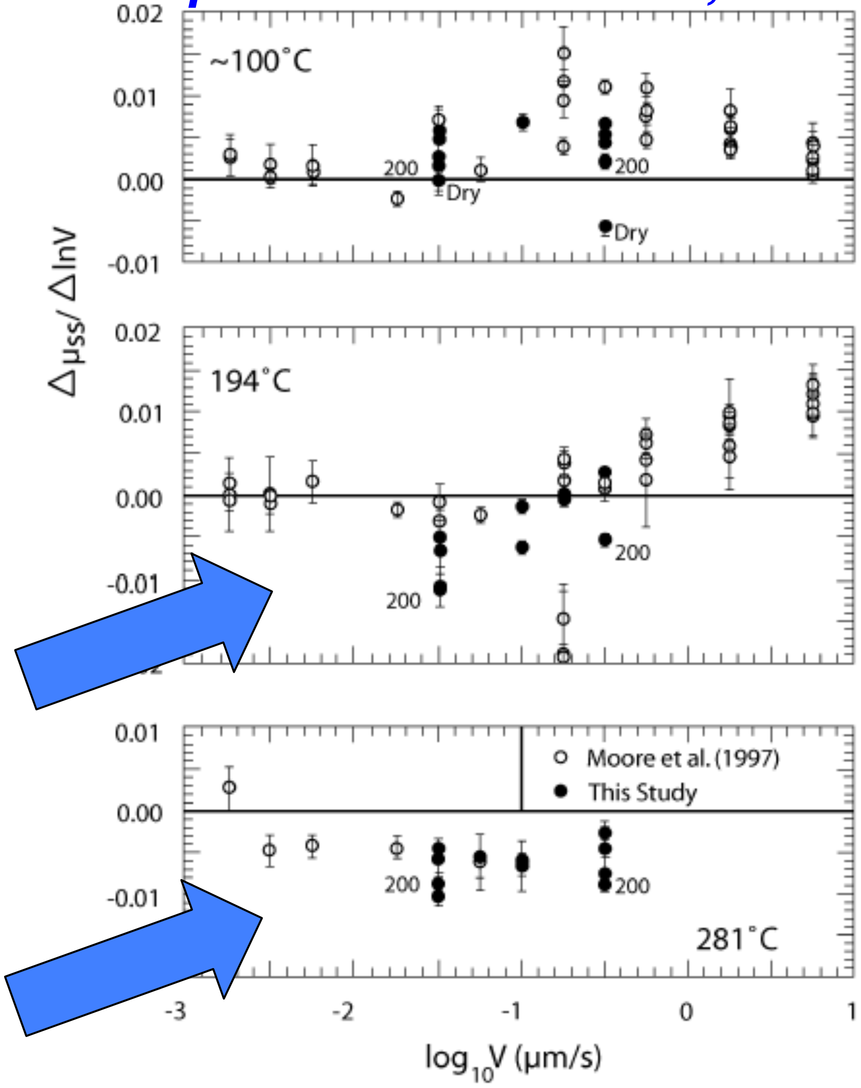
Courtesy of NOAA Ocean Explorer

Frictional Stability of Oceanic Crust

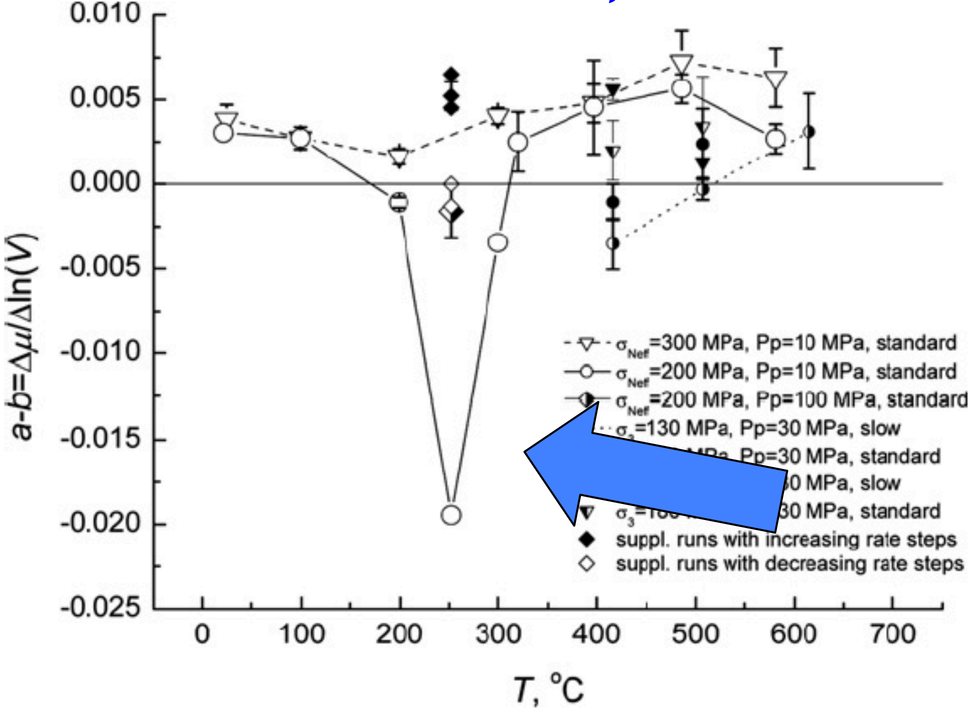
He, et al., Tectonophysics, 2007; Moore et al., Int. Geology Review, 2004; Moore & Lockner, 2008

- Gabbro and Serpentine are velocity weakening at T > ~200˚C;
- Talc is always velocity strengthening

Serpentine- Moore et al., 2004



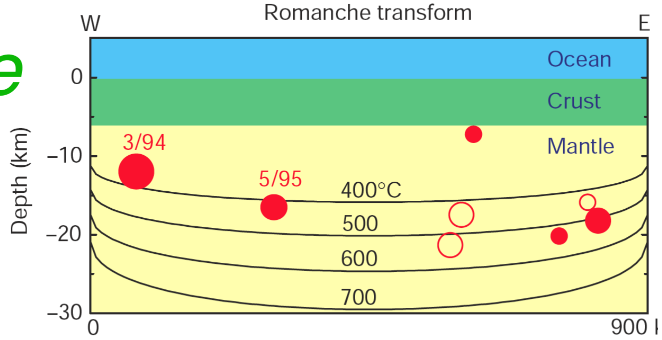
Gabbro- He et al., 2007



Frictional Stability of Oceanic Mantle

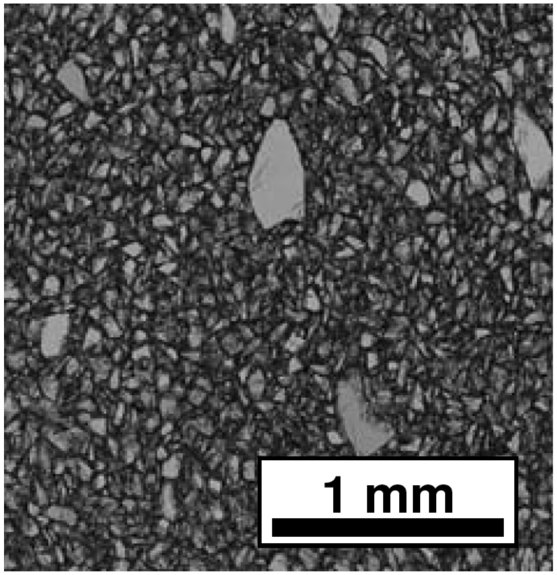
Boettcher, et al., JGR, 2007

Where is the boundary between potentially seismogenic conditions and those that will only produce stable slip?



Abercrombie and Ekström, Nature, 2001

Starting Material



Experimental Conditions

Sample Material: olivine powder < 60 µm

Temperature: 600, 800, & 1000˚C

Pressure: 50, 100, 200, & 300 MPa

Pore Fluids: dry=argon & wet=water

Loading Rate: 0.06 to 60 µm/s

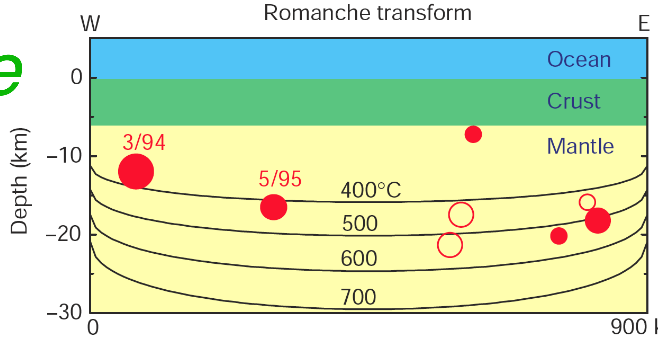
Strain Rate: 3e-6 to 3e-3 s^{-1}

(V = 30 mm/yr ➔ strain rate of 1e-12 s^{-1})

Frictional Stability of Oceanic Mantle

Boettcher, et al., JGR, 2007

Where is the boundary between potentially seismogenic conditions and those that will only produce stable slip?



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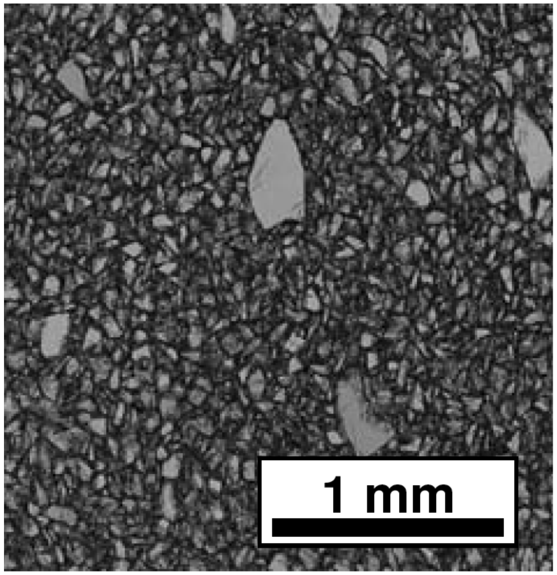
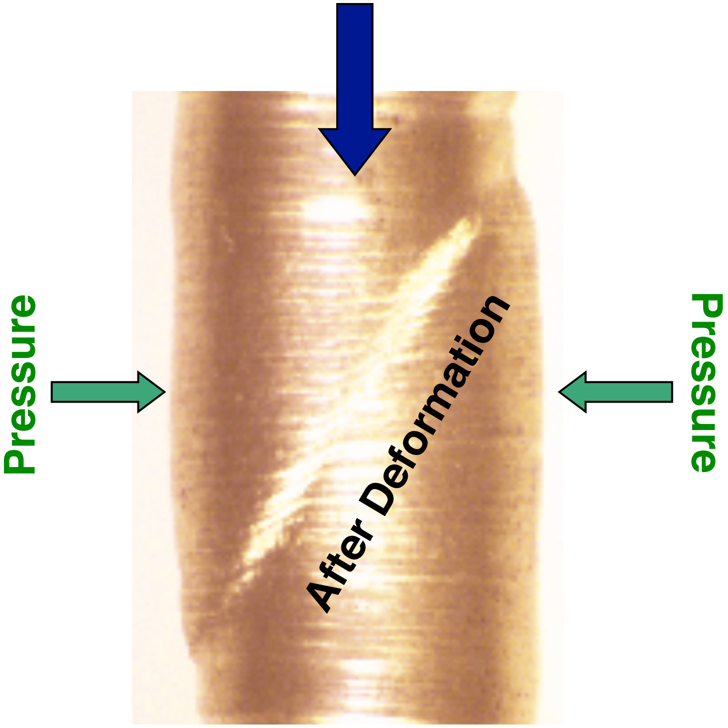




Loading Force

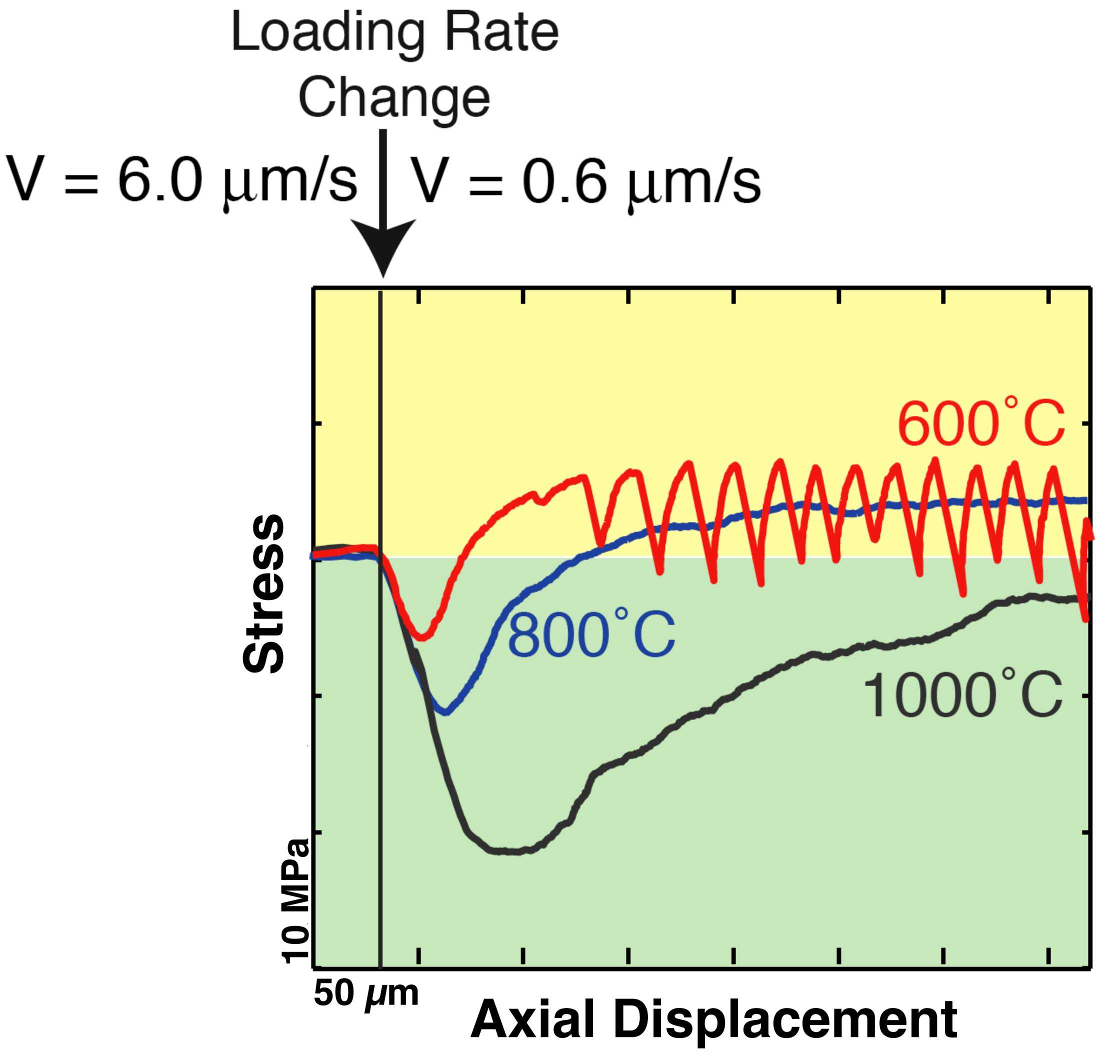
Pressure

After Deformation

Pressure

Frictional Stability of Oceanic Mantle

Boettcher, et al., JGR, 2007



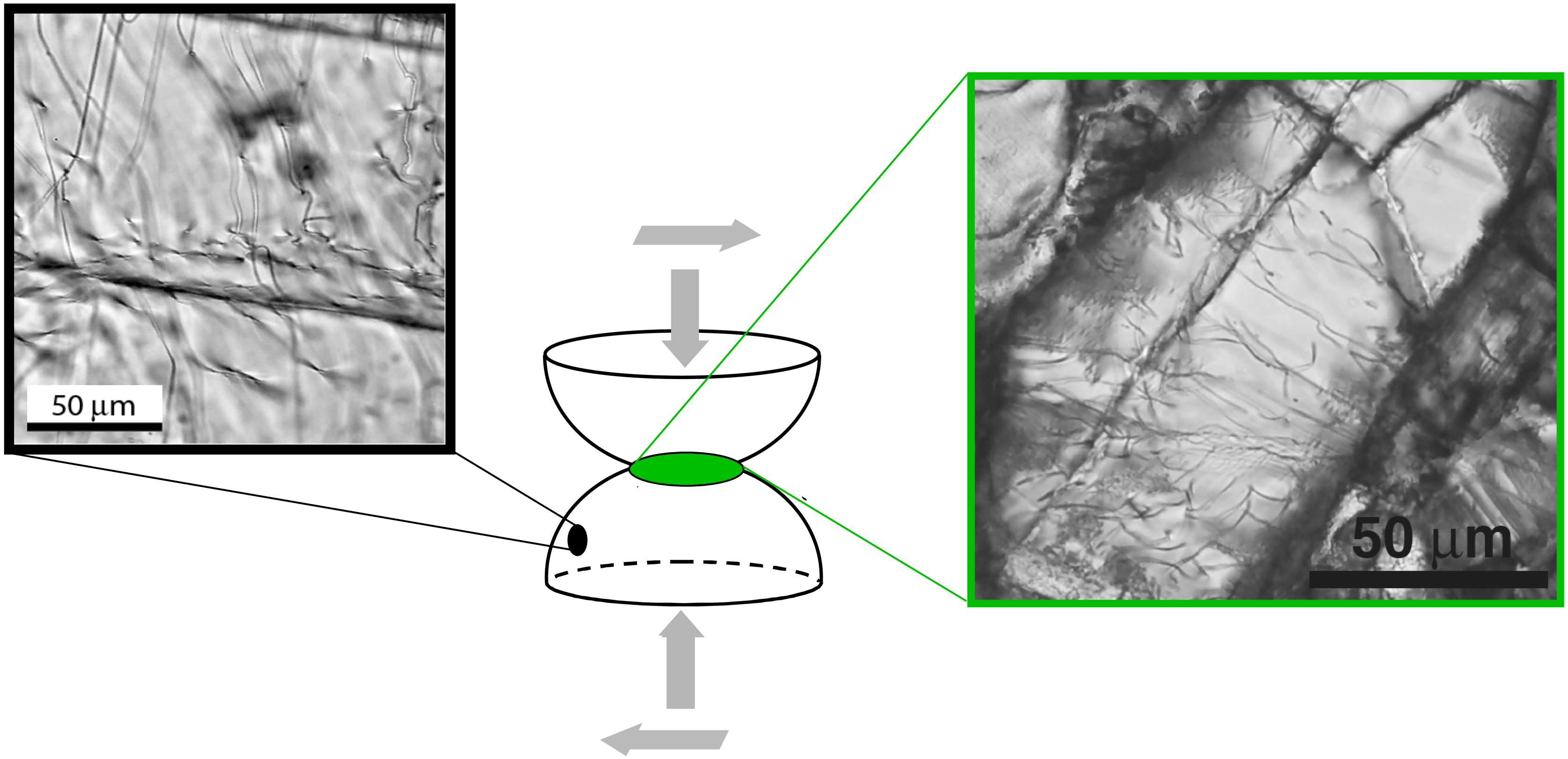
Velocity Weakening
(potentially unstable)

Velocity Strengthening
(stable)

Frictional Stability of Oceanic Mantle-Creep at Asperities

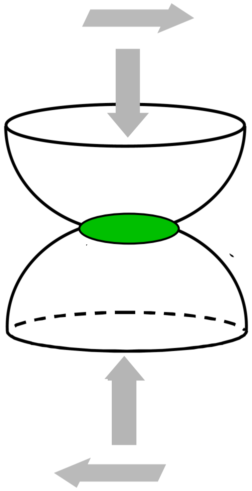
Boettcher, et al., JGR, 2007

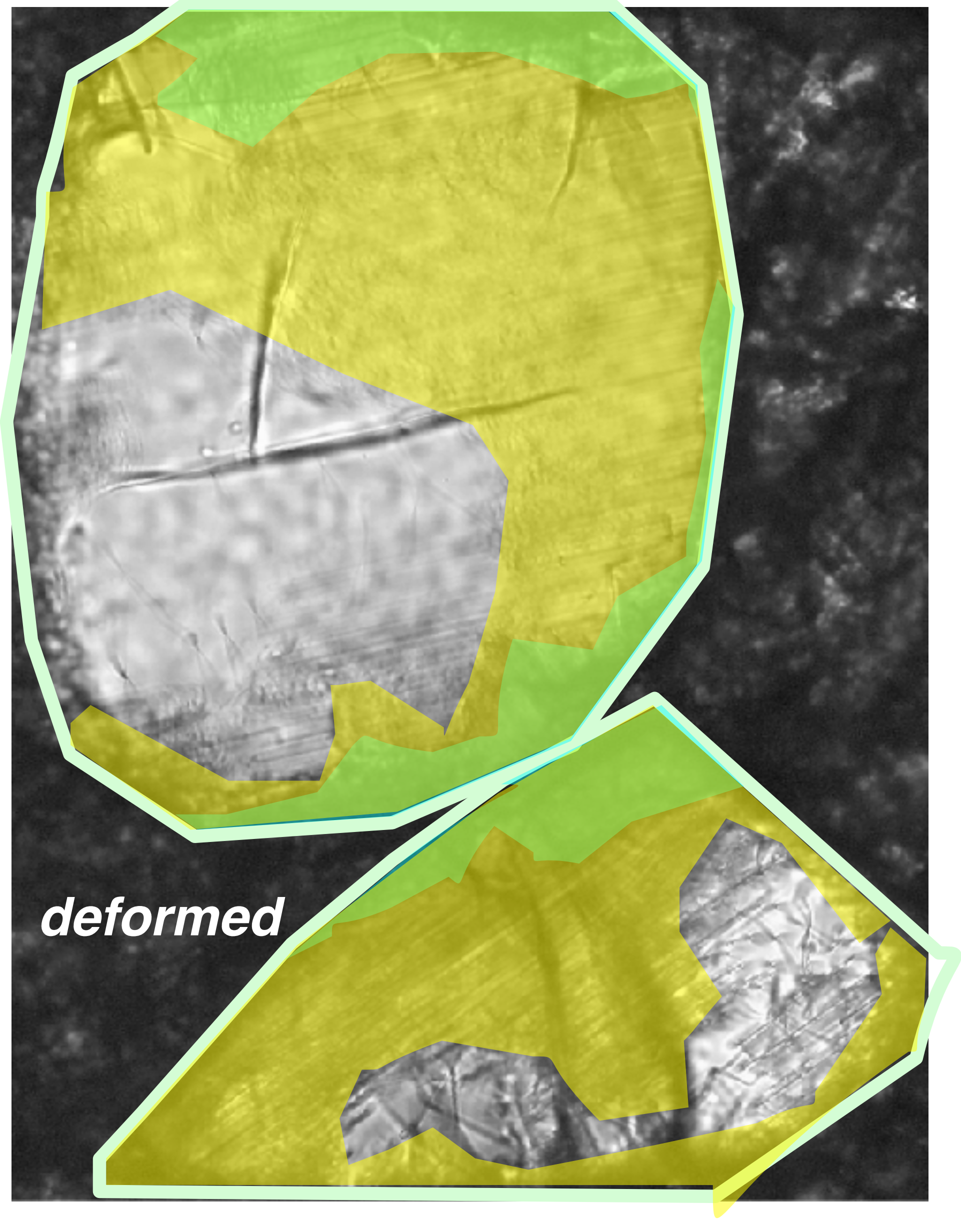
The time and rate dependent processes result from creep of the surface contact and a consequent increase in the real area of contact over time.

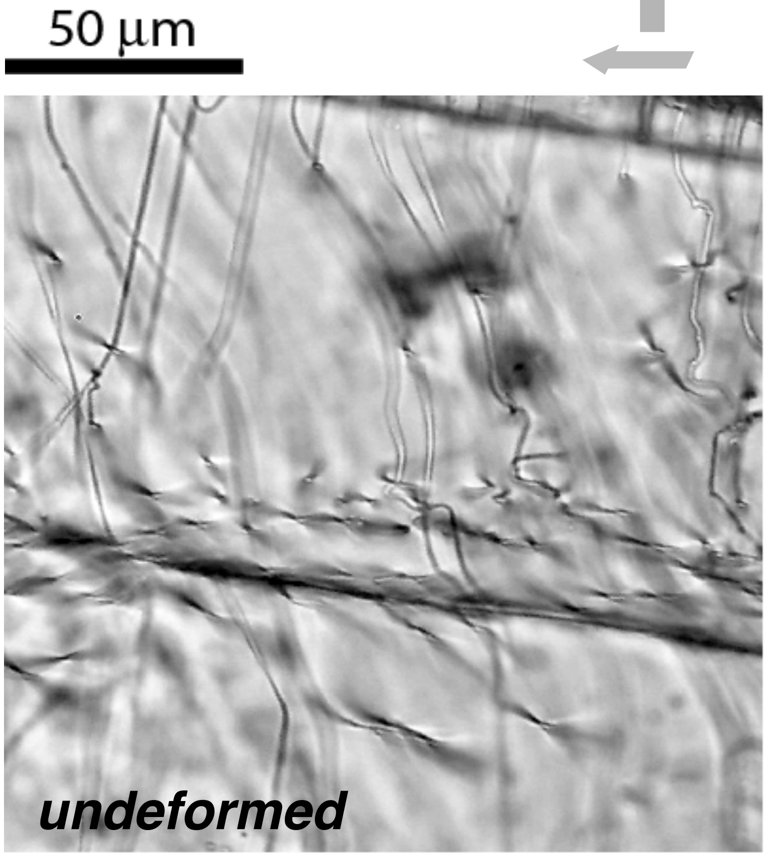


Olivine Friction Experiments- Creep at Asperities

Boettcher, et al., JGR, 2007

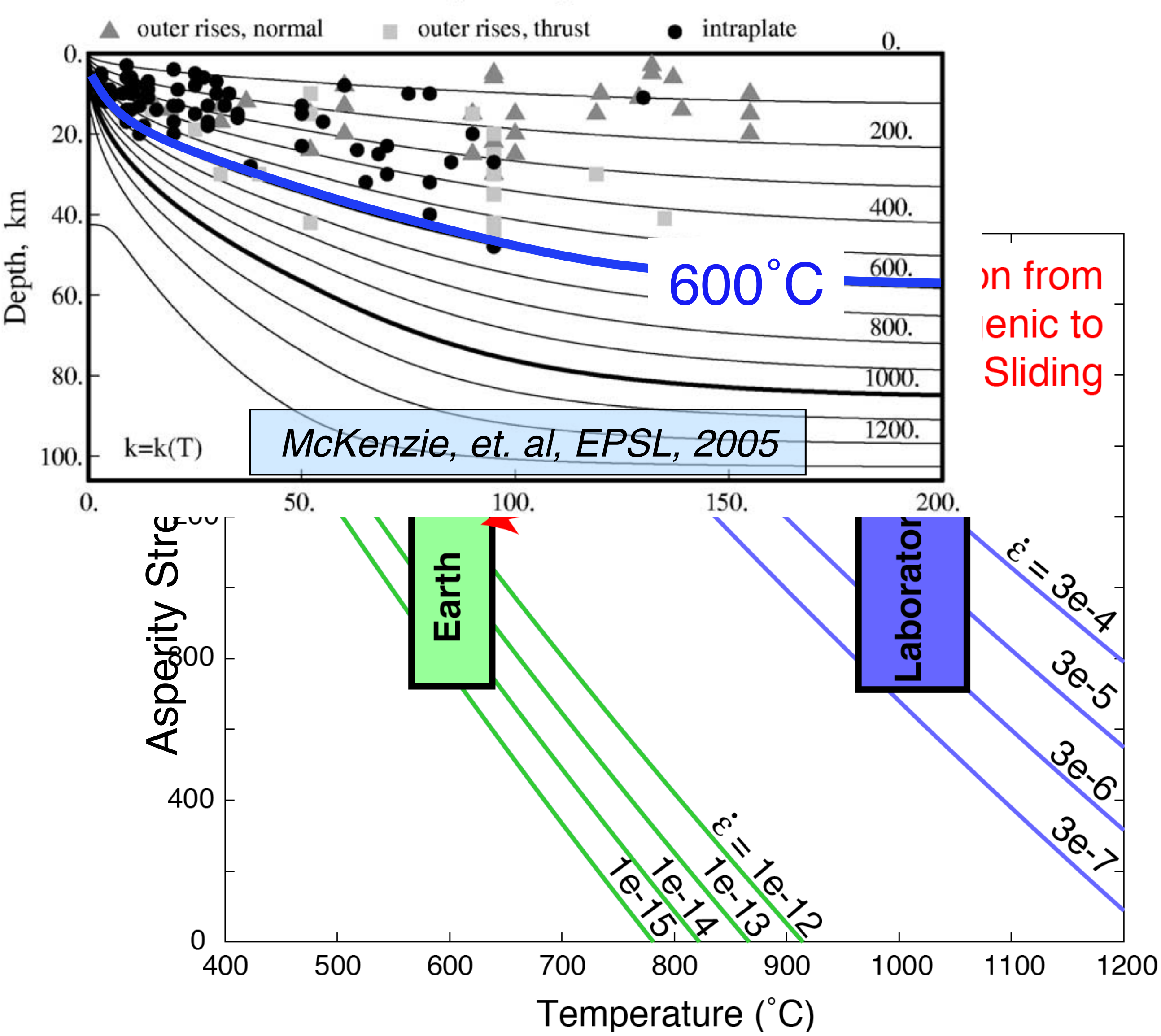


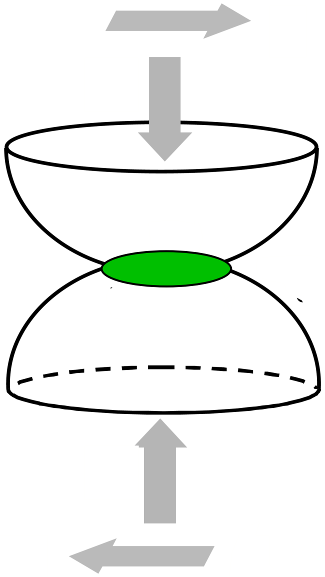




Frictional Stability of Oceanic Mantle

Boettcher, et al., JGR, 2007



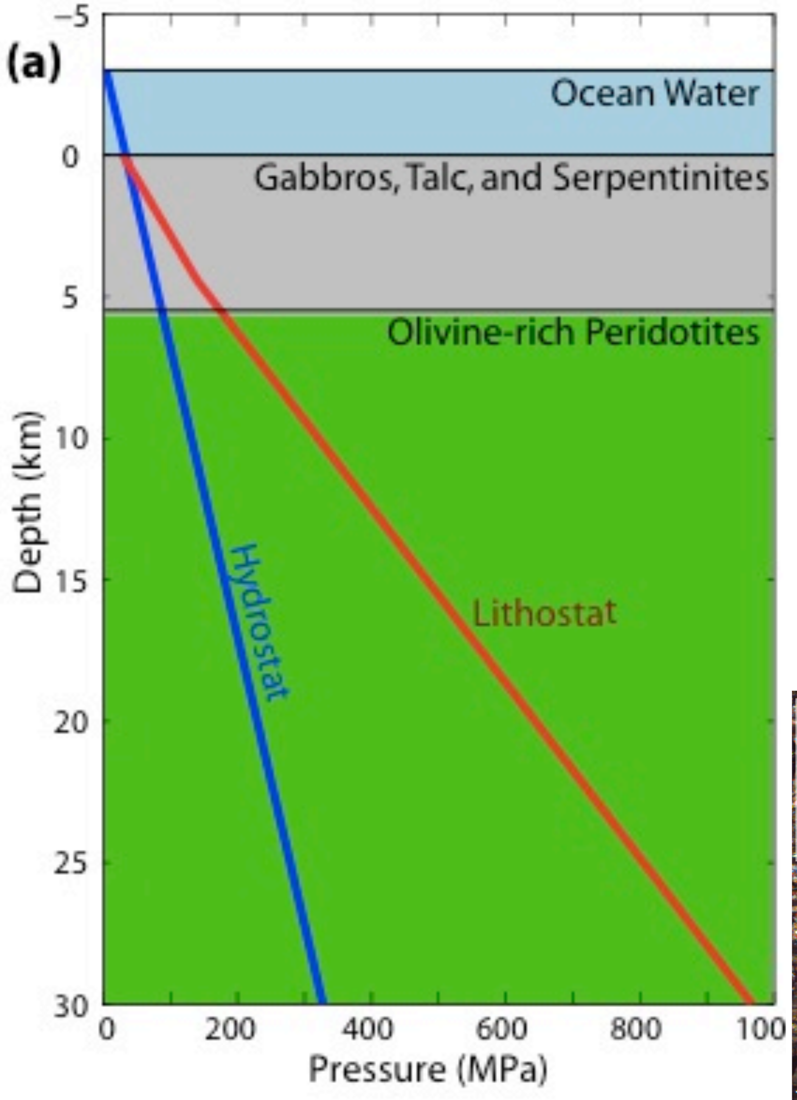


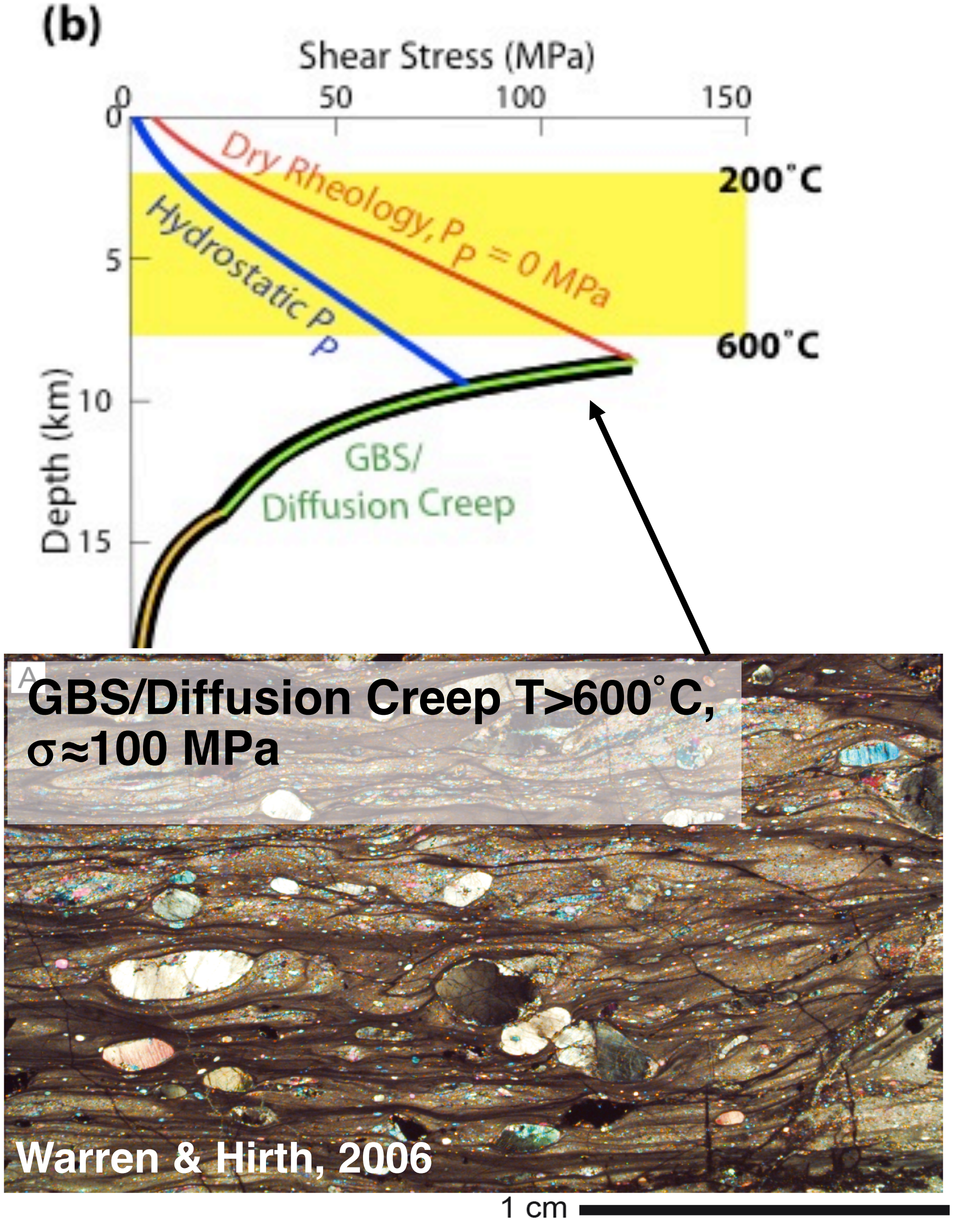
$$\sigma_A = \sigma_P(1+(RT\ln(\dot{\varepsilon})/HB))^{1/q}$$

(Goetze, 1978)

σ_A= Asperity Stress
σ_P= Peierl's Stress
R = Gas Constant
T = Temperature
H = Activation Enthalpy
q, B = Empirical Constants

Oceanic Transform Fault Rheological Model:





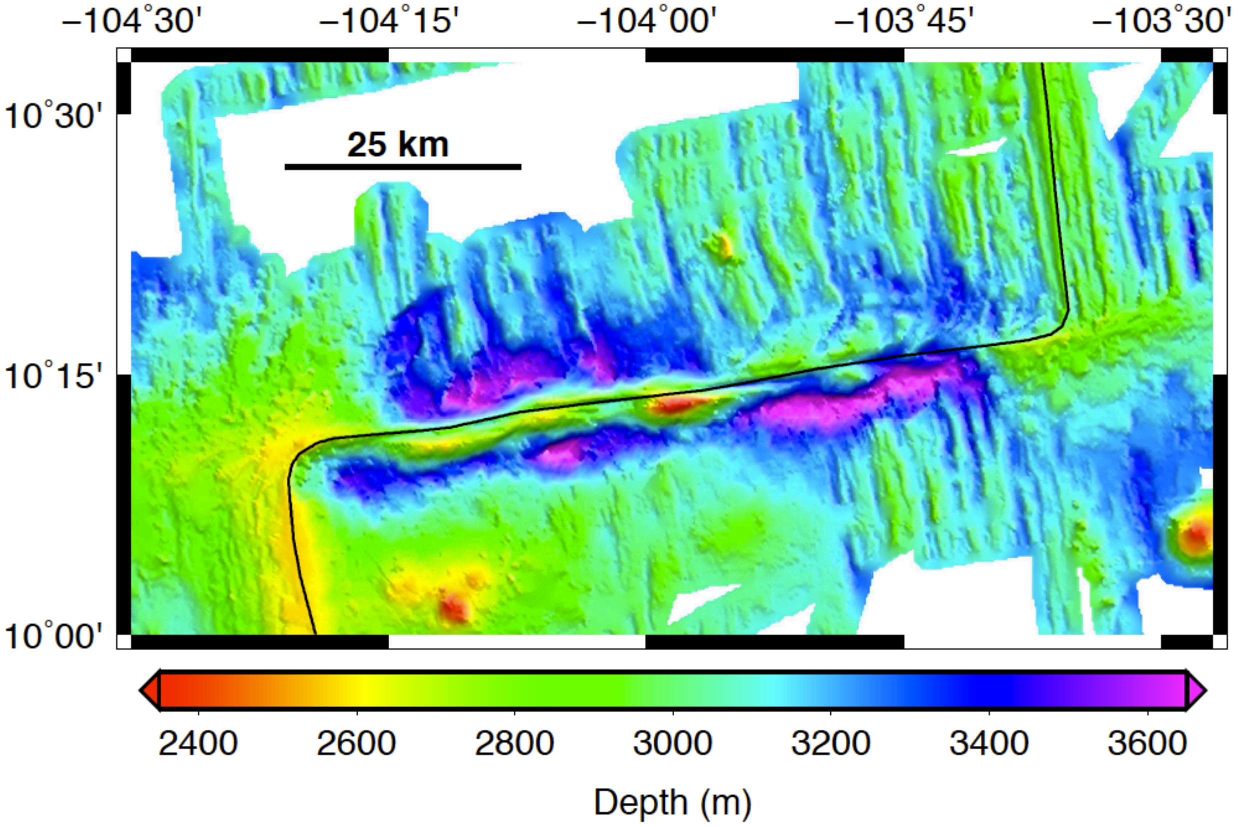
GBS/Diffusion Creep T>600˚C, σ≈100 MPa

Warren & Hirth, 2006

Oceanic Transform Fault Seismicity:

Relatively Predictable Earthquakes

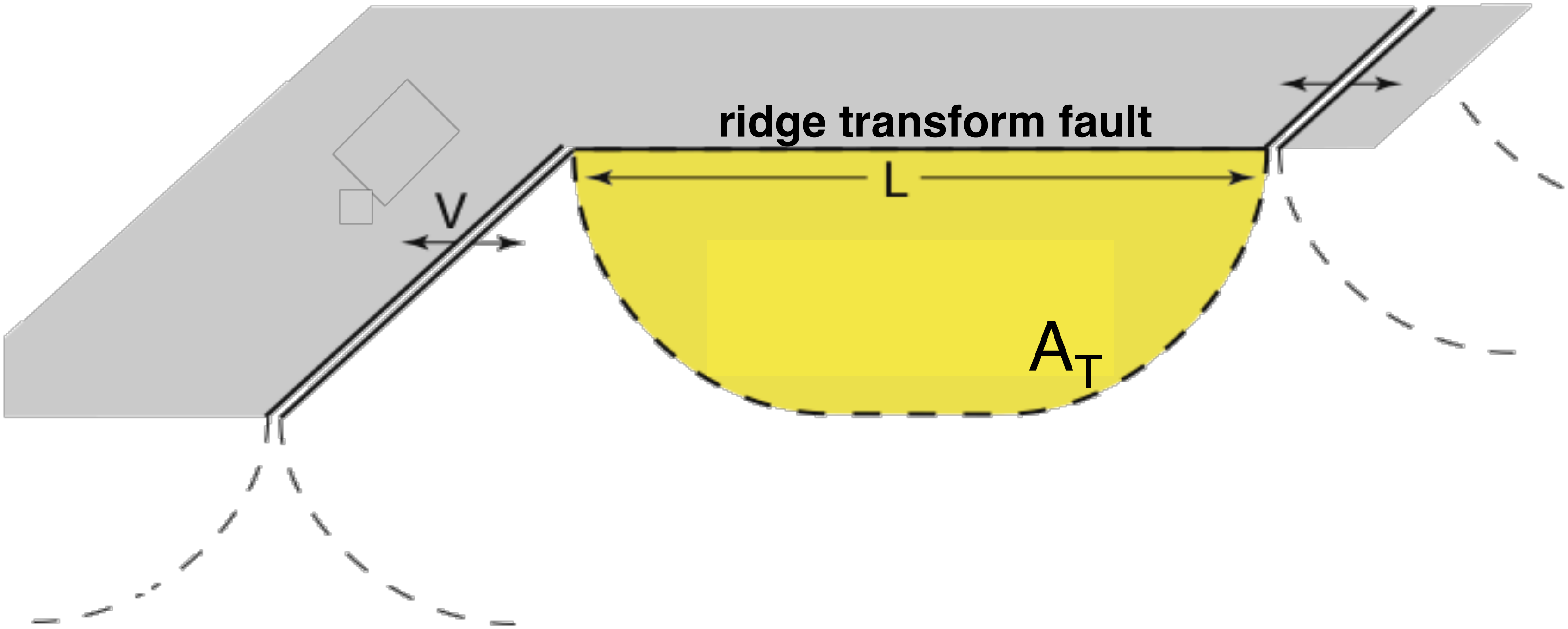
1. Global predictability of earthquake distributions based on scaling relations
2. Long-term predictability as evidenced by stable seismic cycles
3. Short-term Predictability as evidenced by foreshocks



Scaling between Tectonic and Seismic Parameters

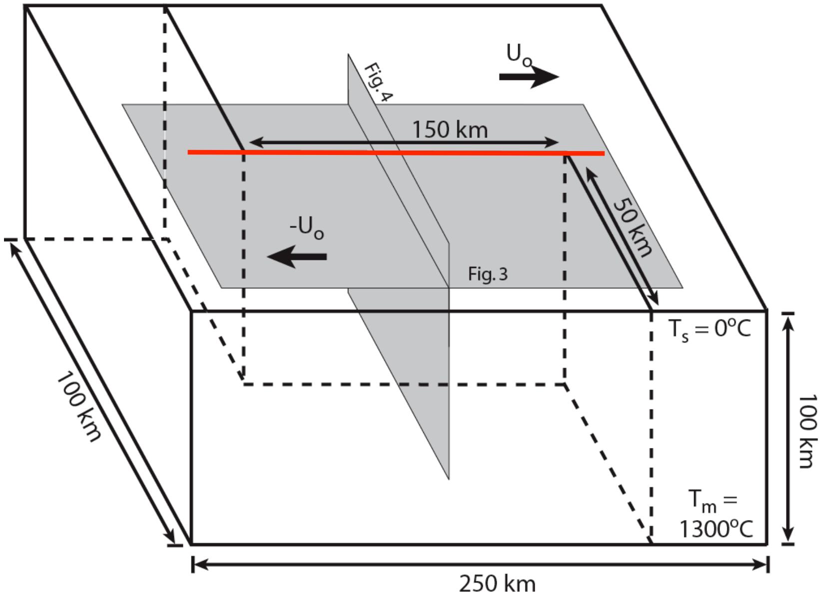
Predictable Fault Thermal Structure:

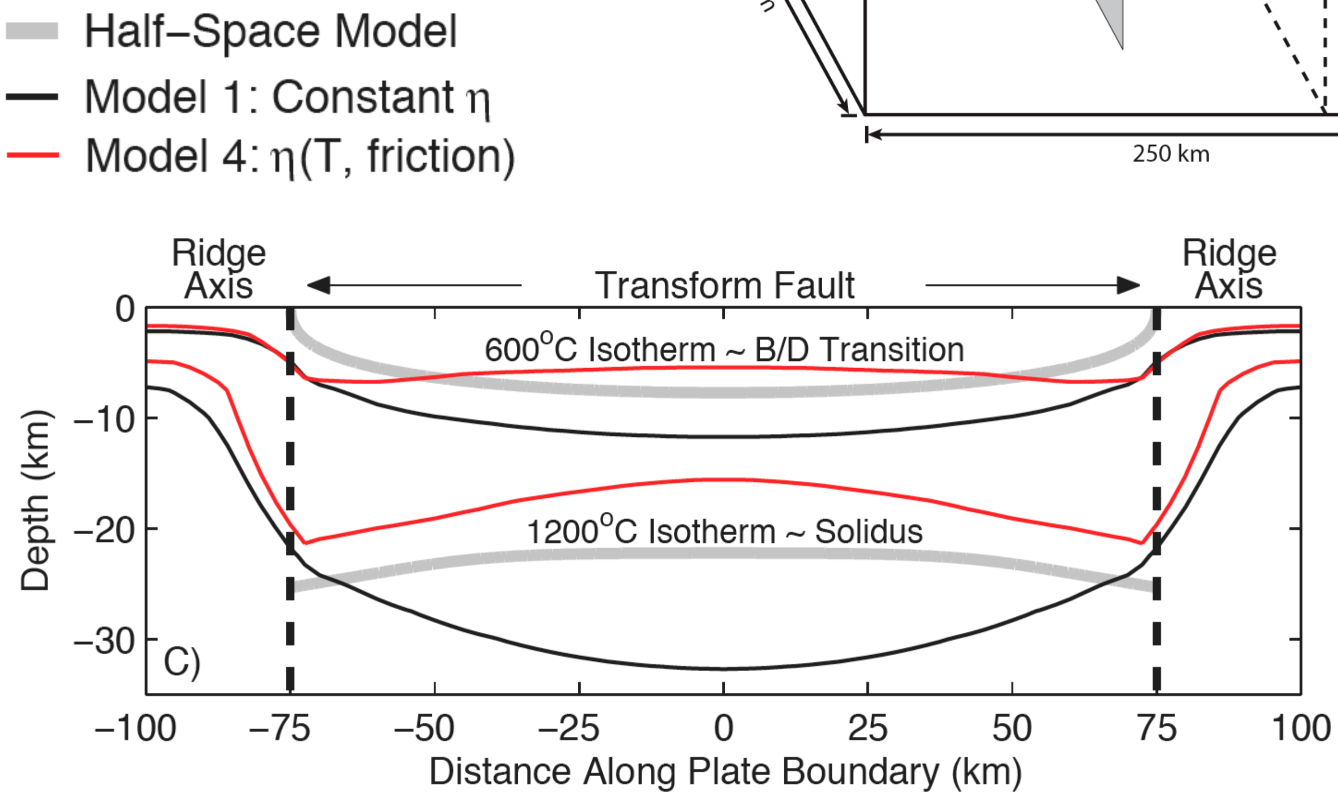
Half-space cooling model: $A_T = C_{ref} L^{3/2} V^{-1/2}$



Transform Fault Thermal Structure

Behn, et al., Geology, 2007
Roland, et al., G-Cubed, 2010





$$\eta = \eta_o \left[\frac{\exp(Q_o / RT)}{\exp(Q_o / RT_m)} \right]$$

$$\tau_{\max} = C_o + \mu \rho g z$$

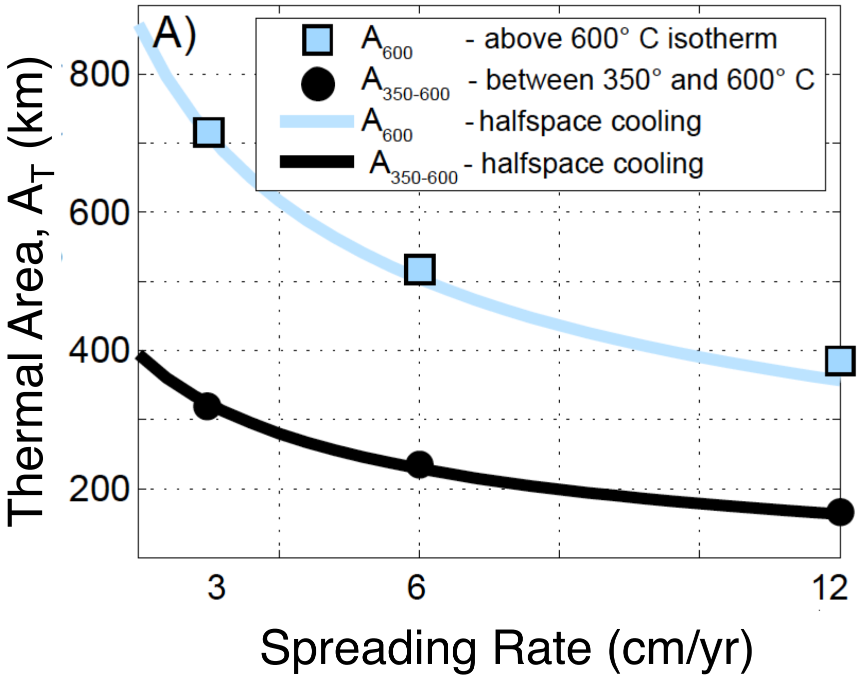
$$\eta = \frac{\tau_{\max}}{\sqrt{2 \dot{\varepsilon}_{II}}}$$

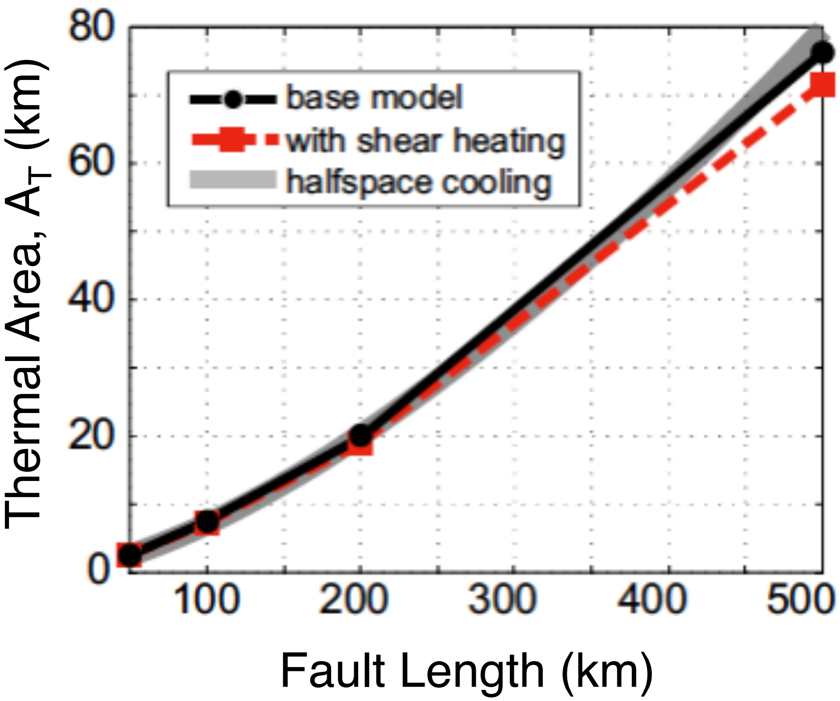
Transform Fault Thermal Structure

Behn, et al., Geology, 2007
Roland, et al., G-Cubed, 2010

No significant change in A_T from including effects of:

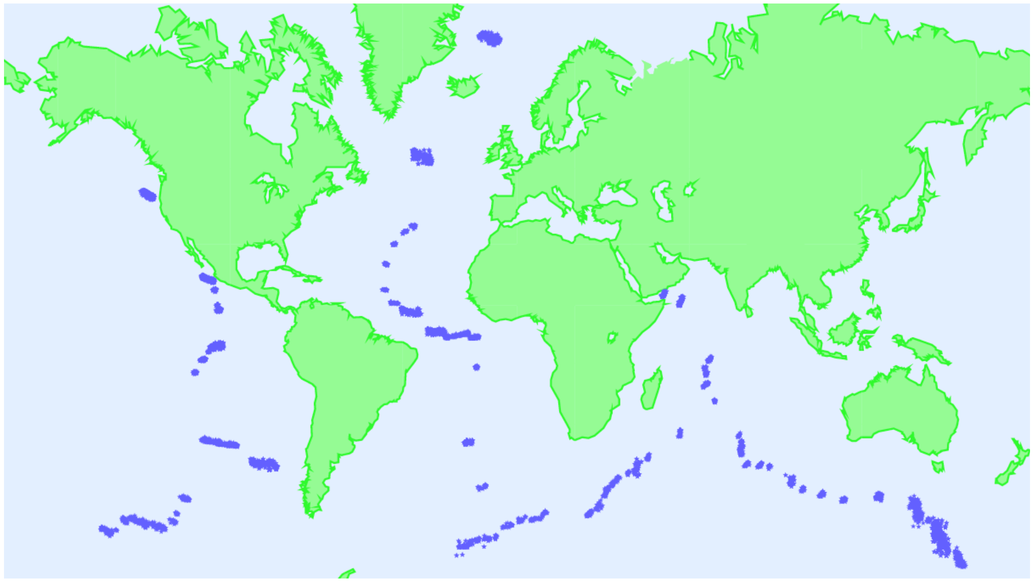
- brittle behavior,
- temperature-dependent rheology,
- shear heating
- hydrothermal cooling





Scaling between Tectonic and Seismic Parameters

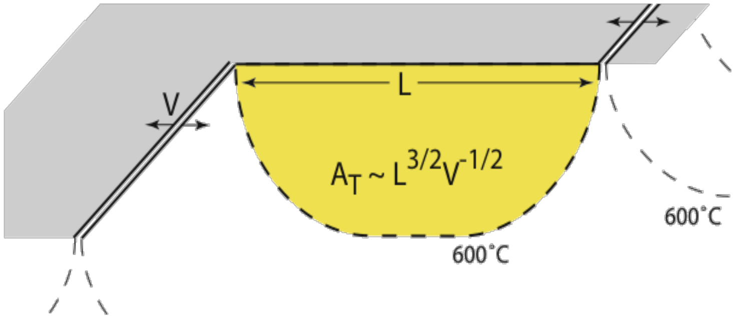
Boettcher and Jordan, JGR, 2004



Tectonic Parameters (L, V, & A_T)

65 Ridge Transform Faults

L ≥ 75 km (totaling≈16,000 km)



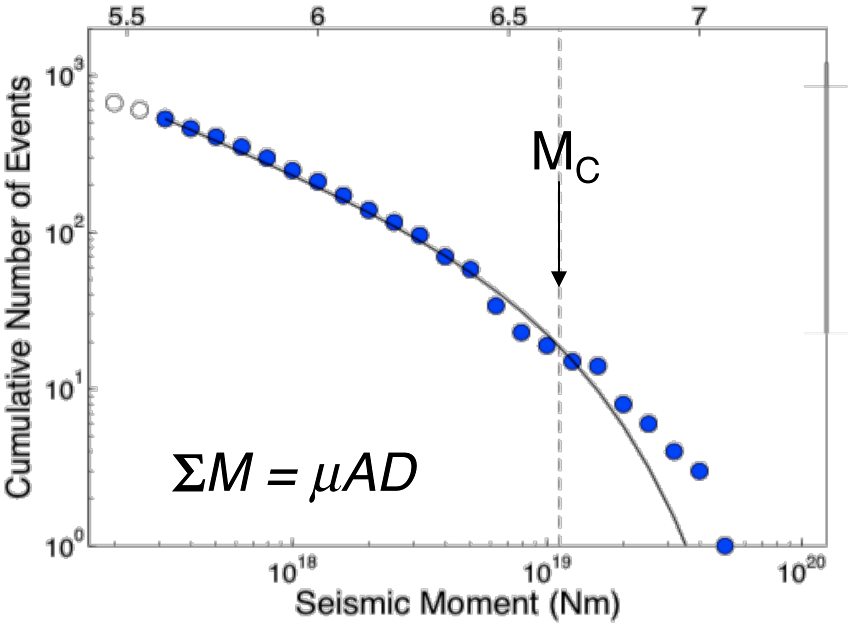
Seismic Parameters (M_C and ΣM)

ISC Catalog 1964-1999

Global CMT 1976-2001

$$N(M) = N_0 \left(\frac{M_0}{M}\right)^3 \exp\left(\frac{M_0 - M}{M_C}\right)$$

(Kagan and Jackson, 2002, GJI)

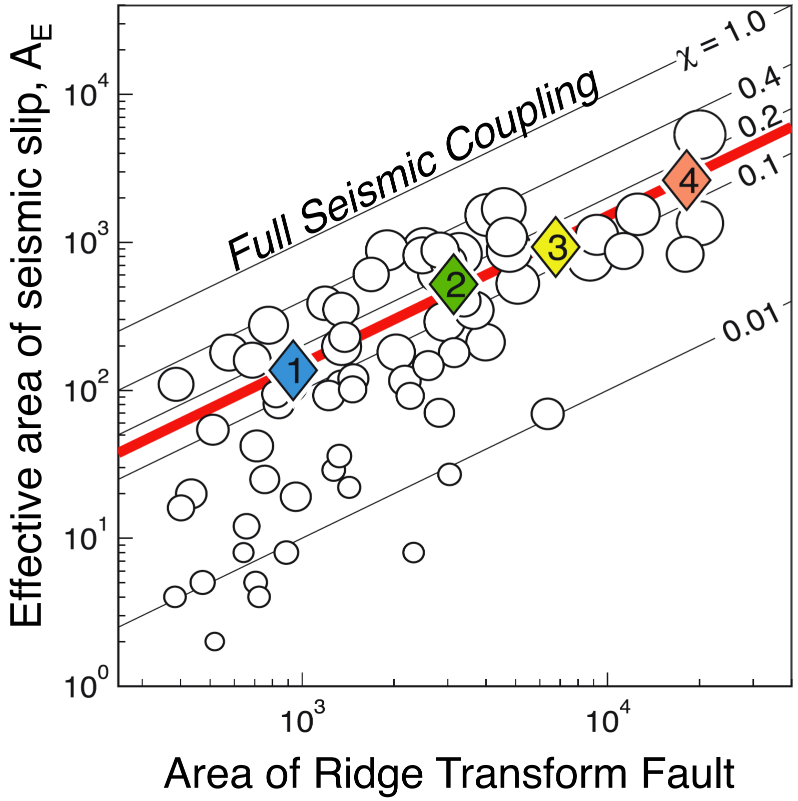


Scaling between Tectonic and Seismic Parameters

Boettcher and Jordan, JGR, 2004

Is there aseismic creep above the 600˚C isotherm during the seismic cycle?

➡ Yes! On average, 85% of the plate motion is aseismic
(or ~65% of the plate motion between 200˚C and 600˚C)

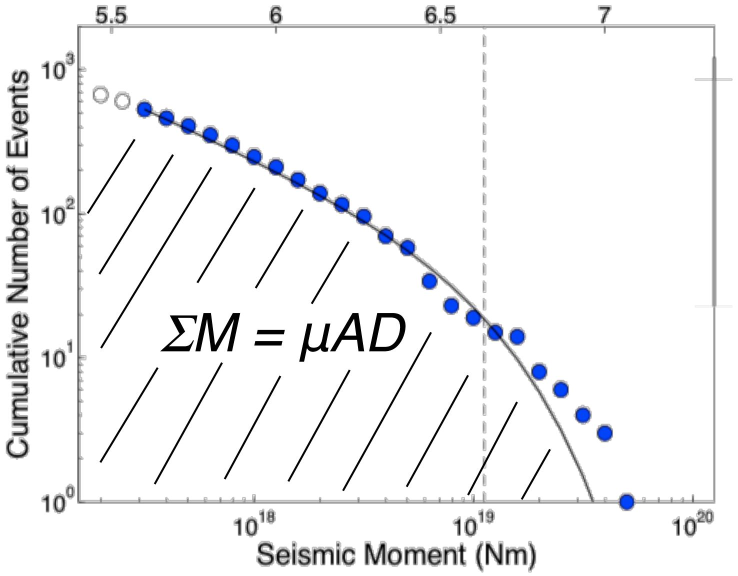


Effective Area of Seismic Slip

$\Sigma M = \mu A D$

$\Sigma M/t = \mu A_E(D/t)$

$\mathbf{A_E = \Sigma M/(t\mu V)}$



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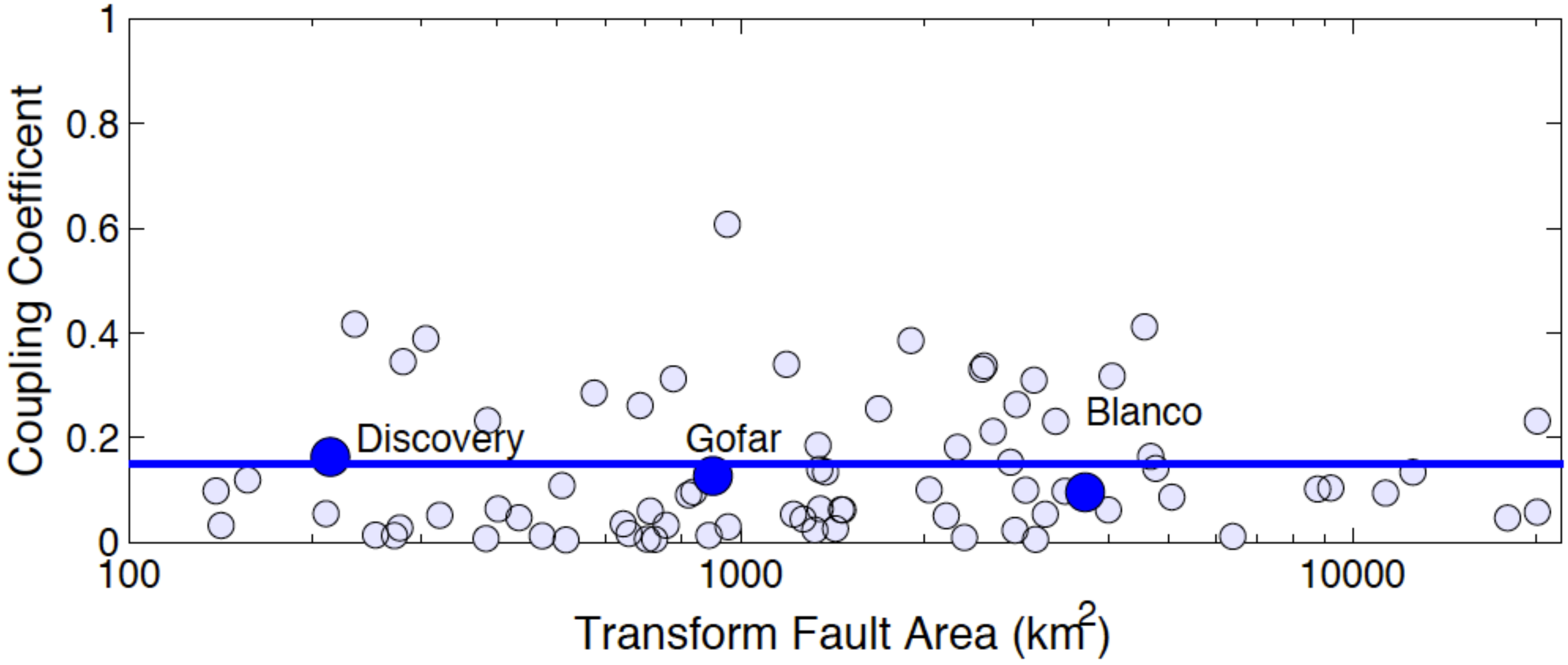
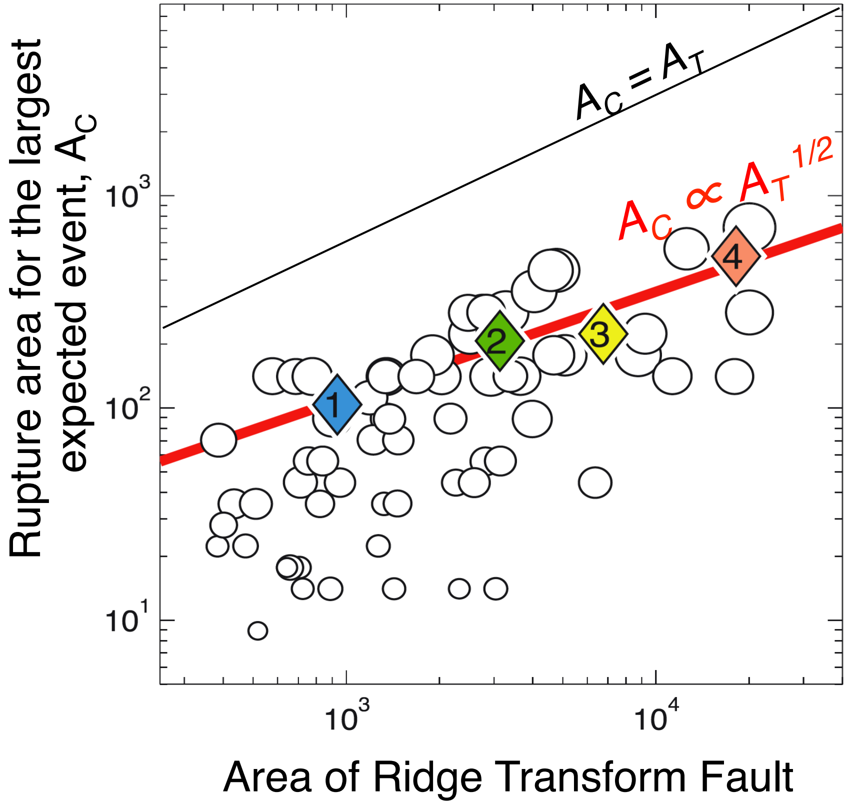


Scaling between Tectonic and Seismic Parameters

Boettcher and Jordan, JGR, 2004

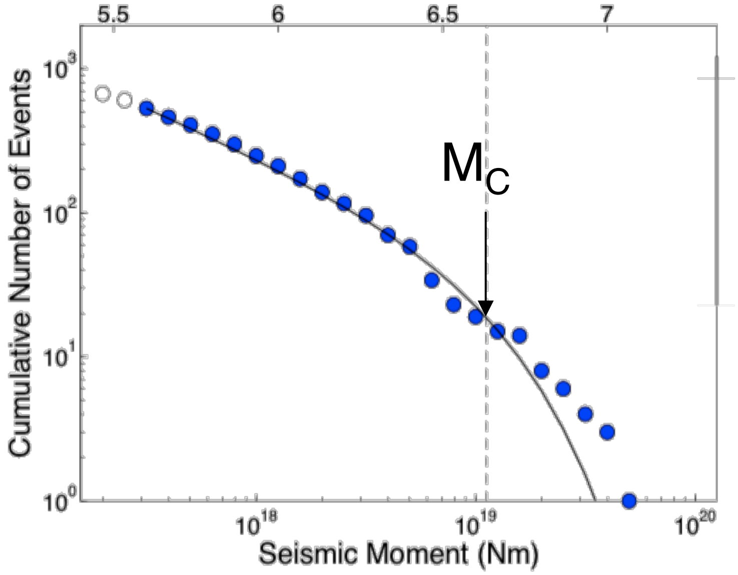
Will the largest expected event (M_C) rupture the total fault area?

➡ No… and furthermore A_C scales as $A_T^{1/2}$
(equivalently, M_C scales as $A_T^{3/4}$)



Rupture Area of Largest Expected Event

$A_C = M_C/\mu D_C$



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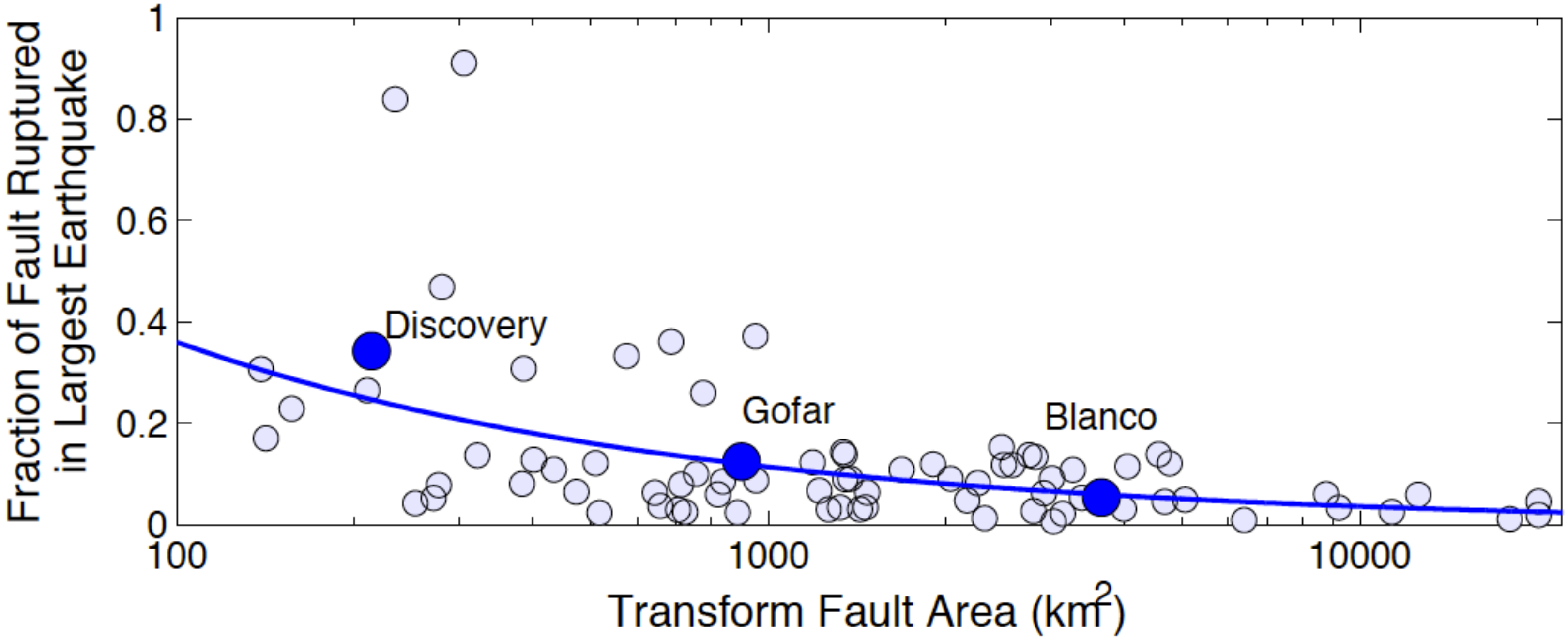
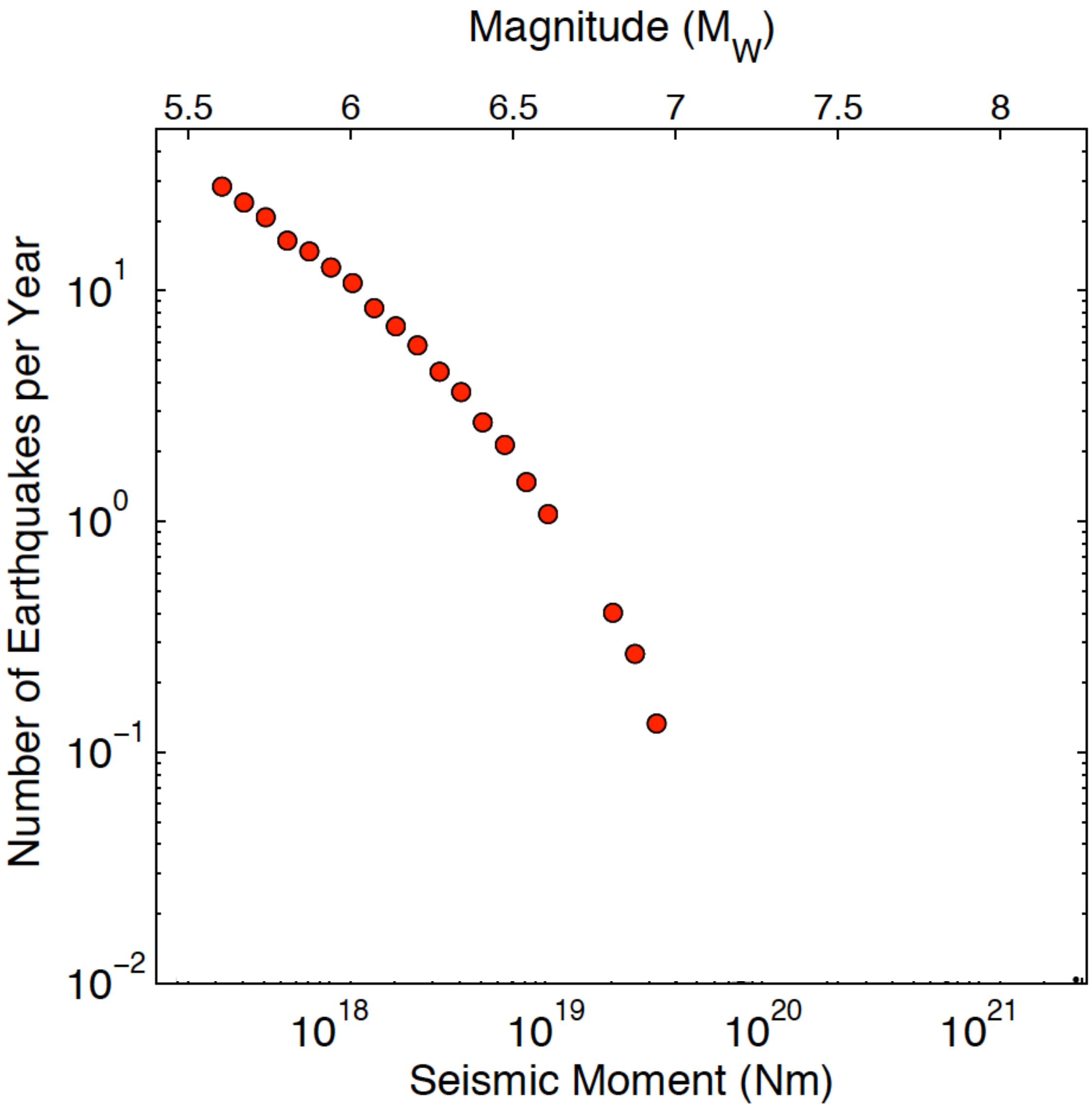


RTF Magnitude Frequency Distribution

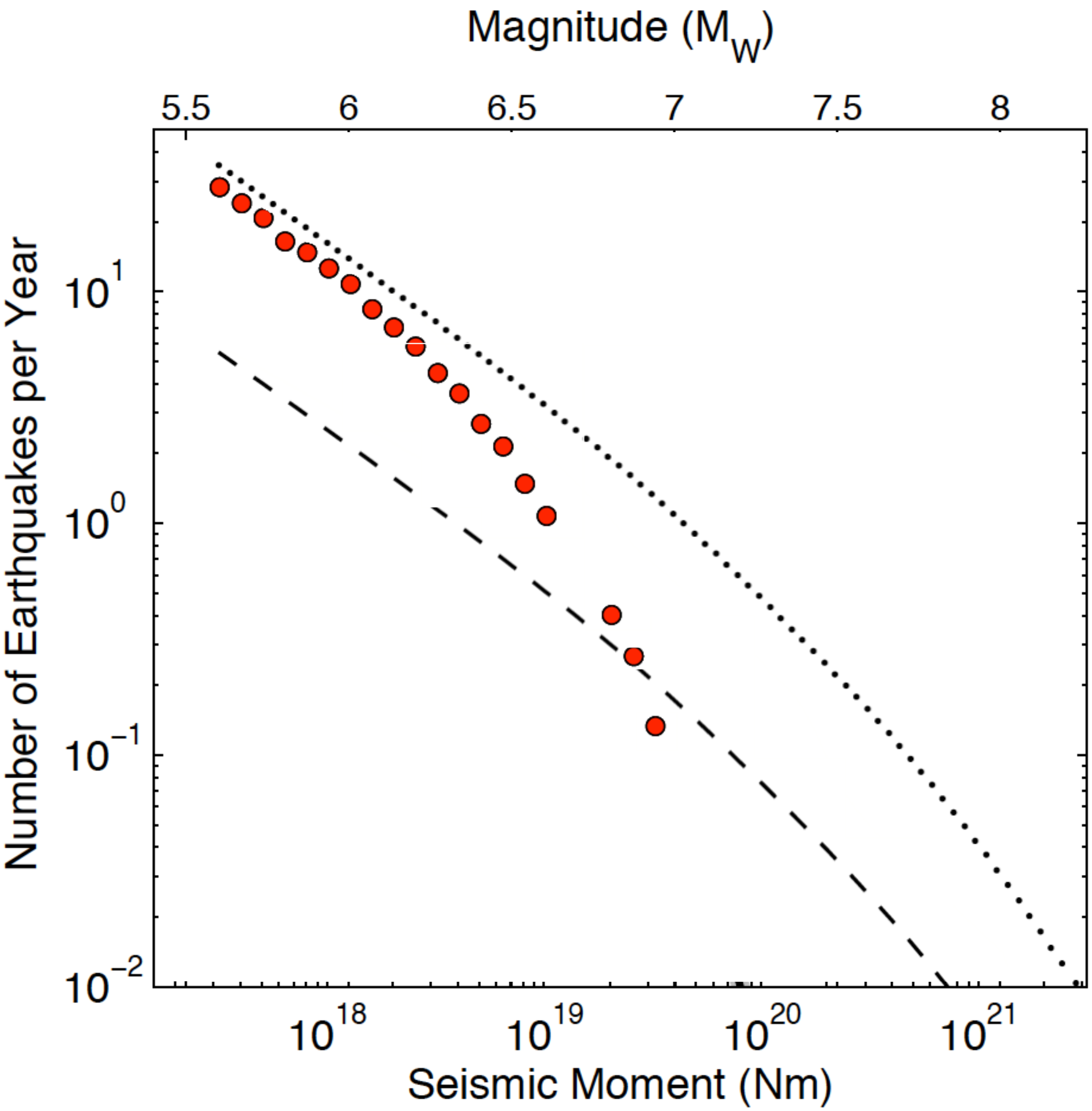
Boettcher and McGuire, GRL, 2009



Data: 2002-2009 RTF earthquakes

RTF Magnitude Frequency Distribution

Boettcher and McGuire, GRL, 2009



Data: 2002-2009 RTF earthquakes

Predicted Distributions:

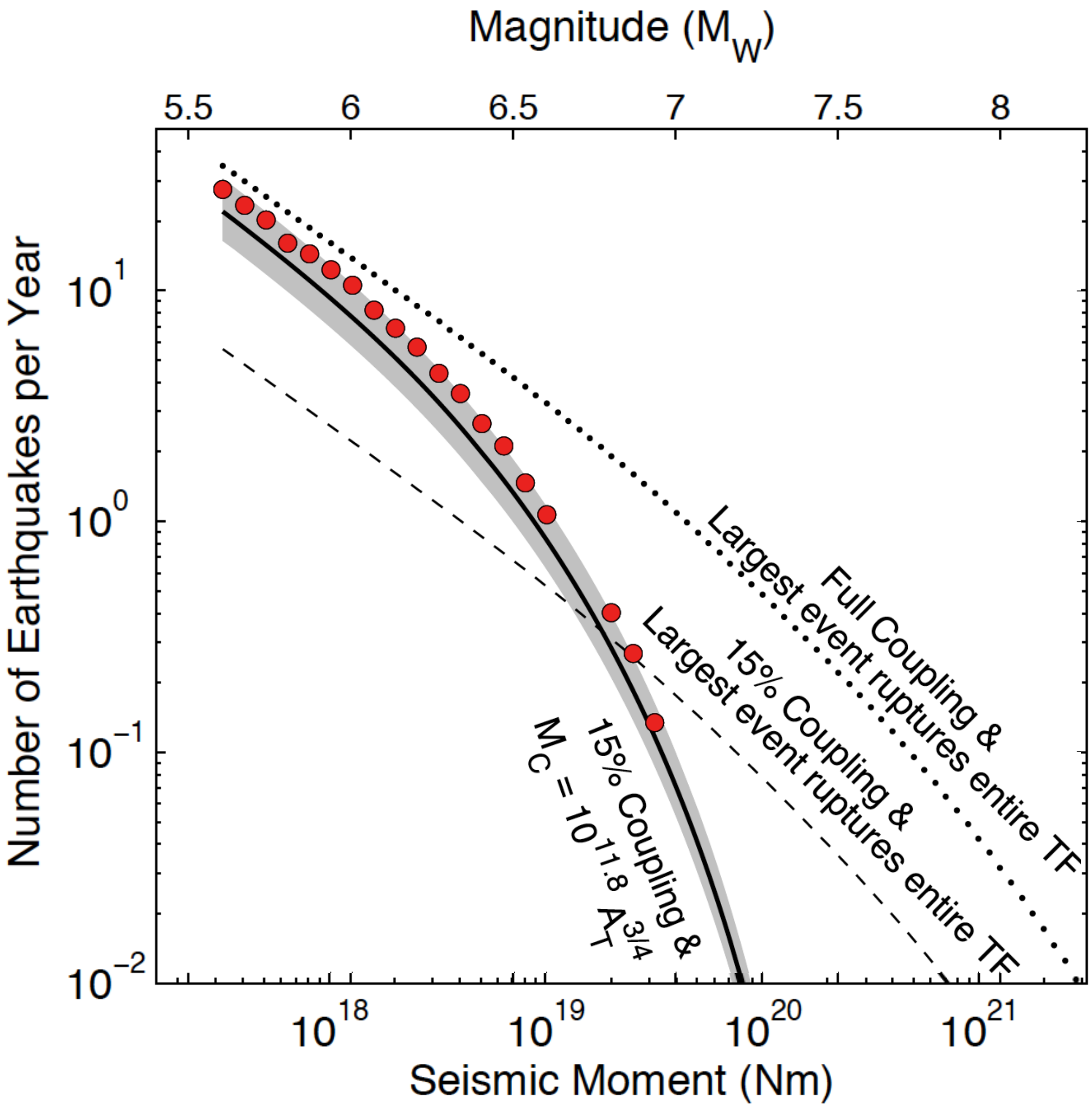
- tapered Gutenberg-Richter distribution
- RTF L’s & V’s

- *No aseismic slip*
- *Largest earthquake ruptures the entire fault*

- *85% of slip is aseismic*
- *Largest earthquake ruptures the entire fault*

Predicted Magnitude Frequency Distribution!

Boettcher and McGuire, GRL, 2009



Data: 2002-2009 RTF earthquakes

Predicted Distributions:

- tapered Gutenberg-Richter distribution
- RTF L's & V's

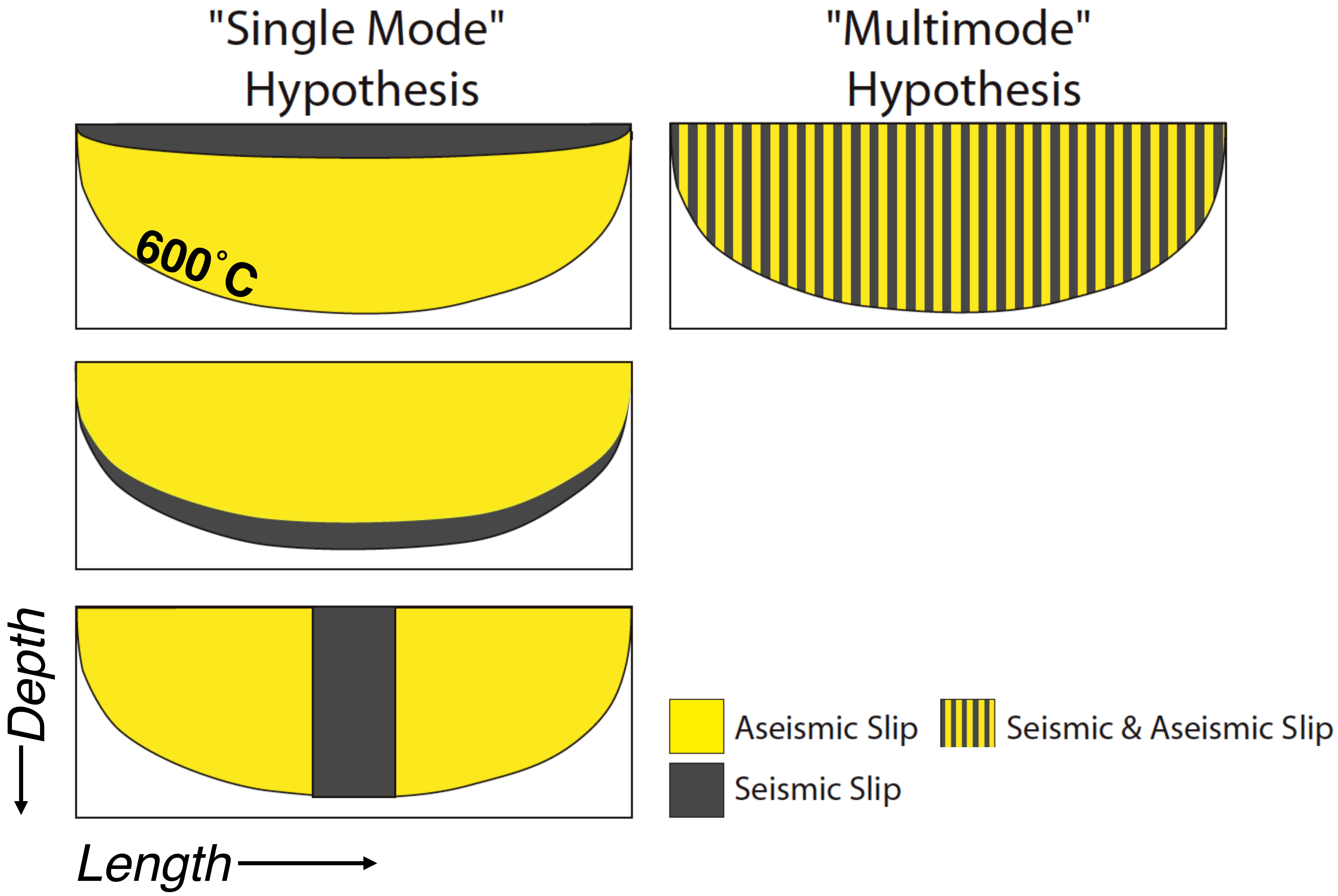
Observed Scaling Relations:

85% of slip is aseismic

The largest expected earthquake scales as the fault area to the 3/4 power

How is slip accommodated on Oceanic Transform Faults?

Boettcher and Jordan, JGR, 2004; Boettcher and McGuire, GRL, 2009

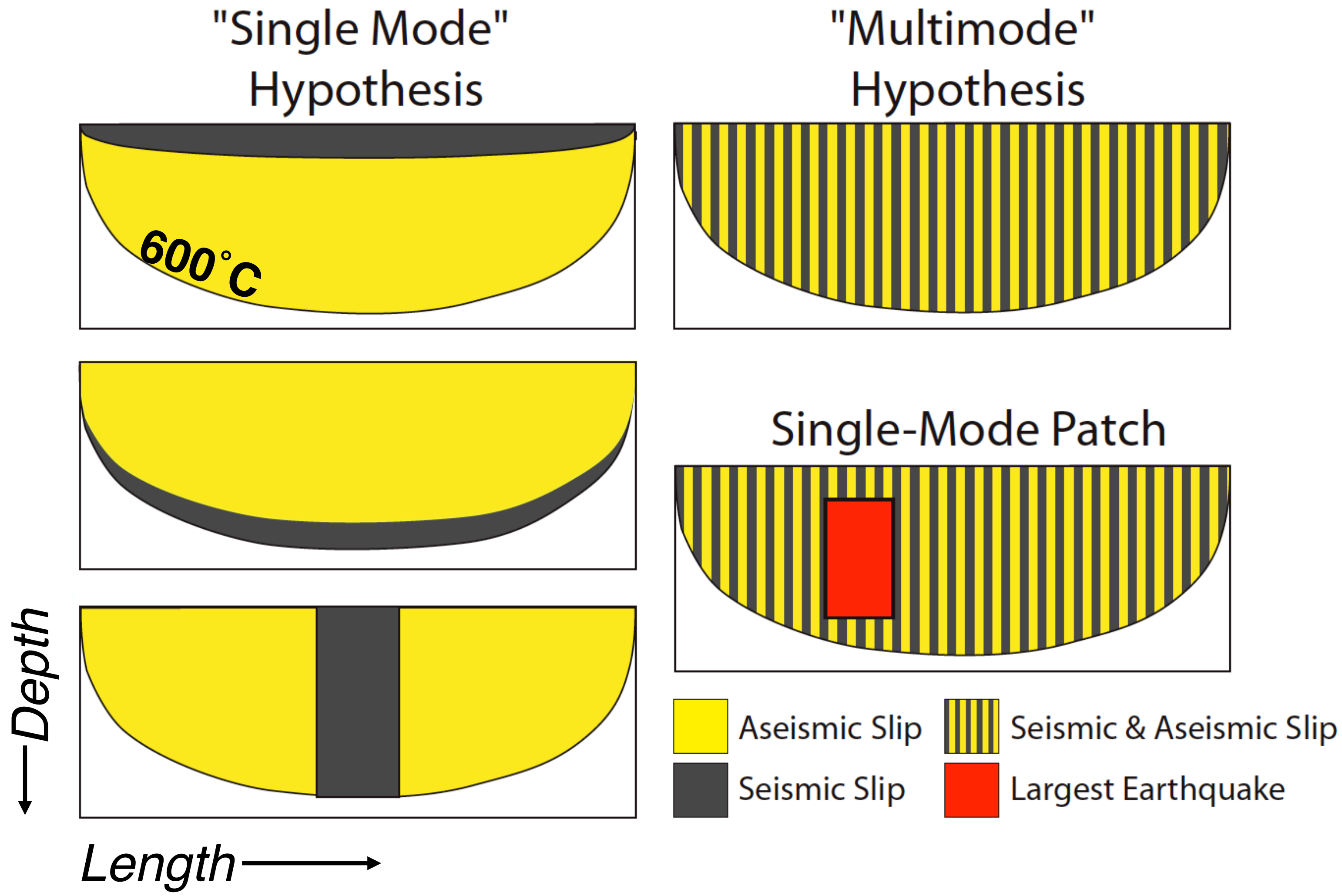


"Single Mode" Hypothesis

"Multimode" Hypothesis

How is slip accommodated on Oceanic Transform Faults?

Boettcher and Jordan, JGR, 2004; Boettcher and McGuire, GRL, 2009

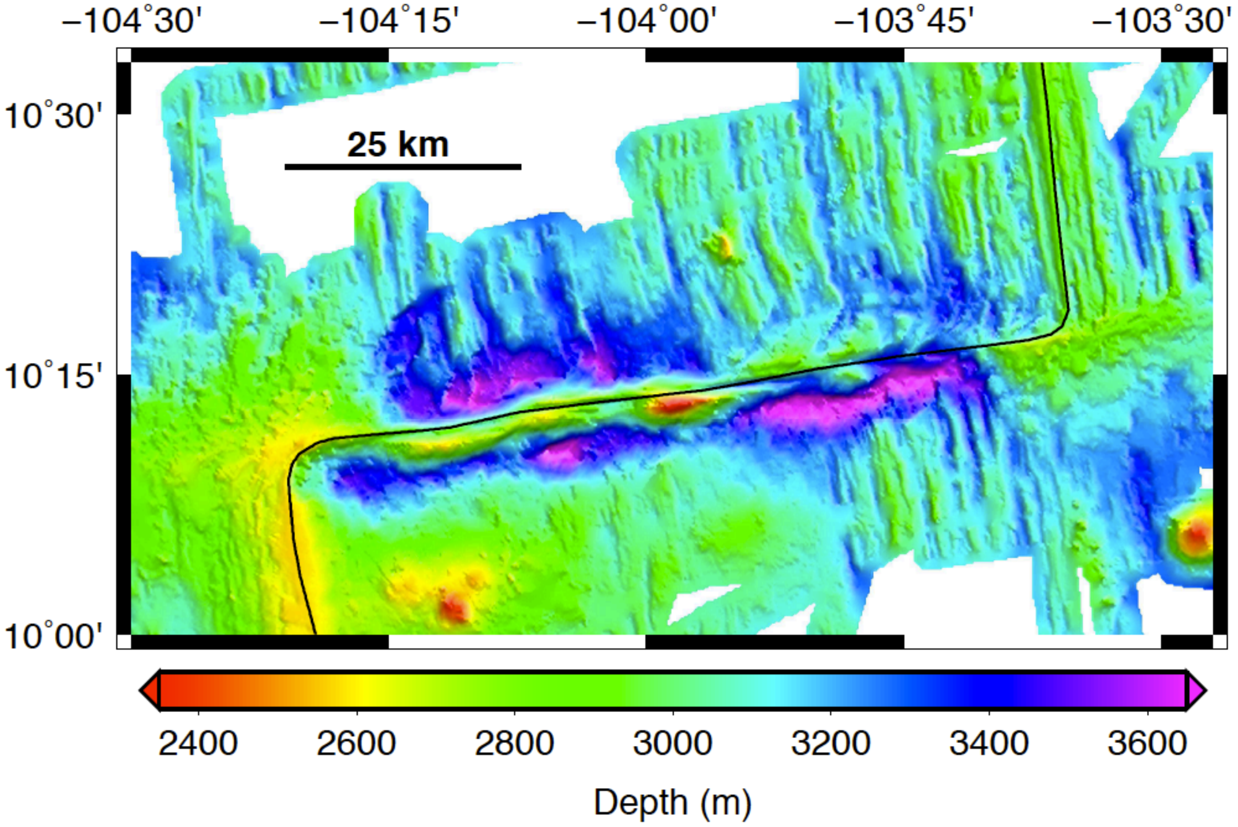


➡ ***Do the largest RTF earthquakes repeatedly rupture the same fault patch?***

Oceanic Transform Fault Seismicity:

Relatively Predictable Earthquakes

1. Global predictability of earthquake distributions based on scaling relations
2. Long-term predictability as evidenced by stable seismic cycles
3. Short-term Predictability as evidenced by foreshocks



Earthquake Cycles: Elastic Rebound Theory

e.g. Reid, 1910

- Timing of the next earthquake depends on the amount of slip since the last one
- Implies full seismic coupling
- Difficult to verify due to long seismic cycles (50-1000 years) and complex fault systems

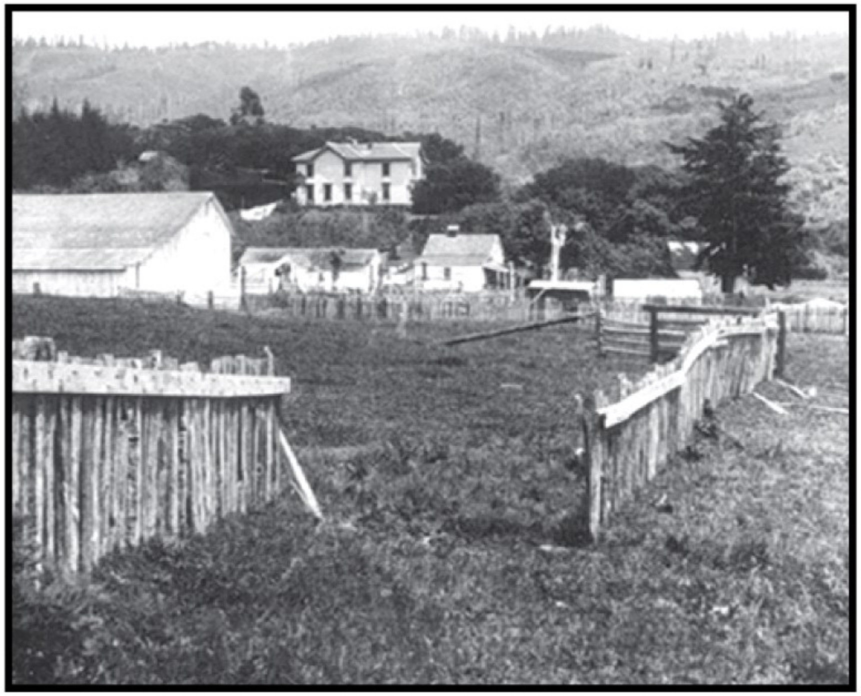
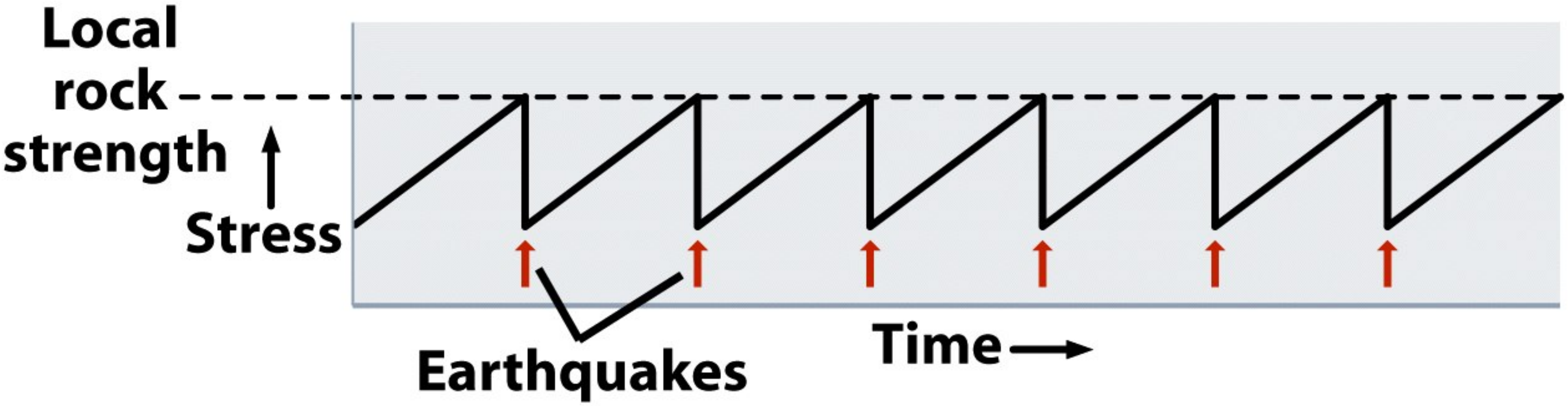


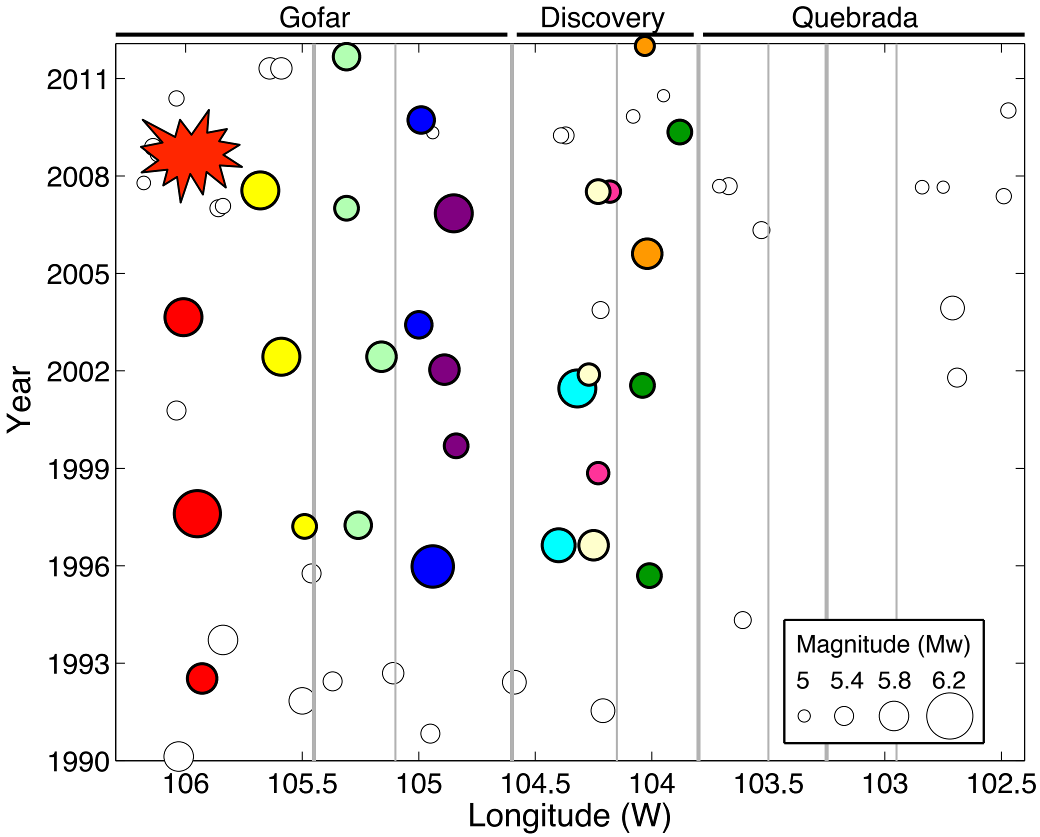
Figure 13-1 part 2b
Understanding Earth, Fifth Edition

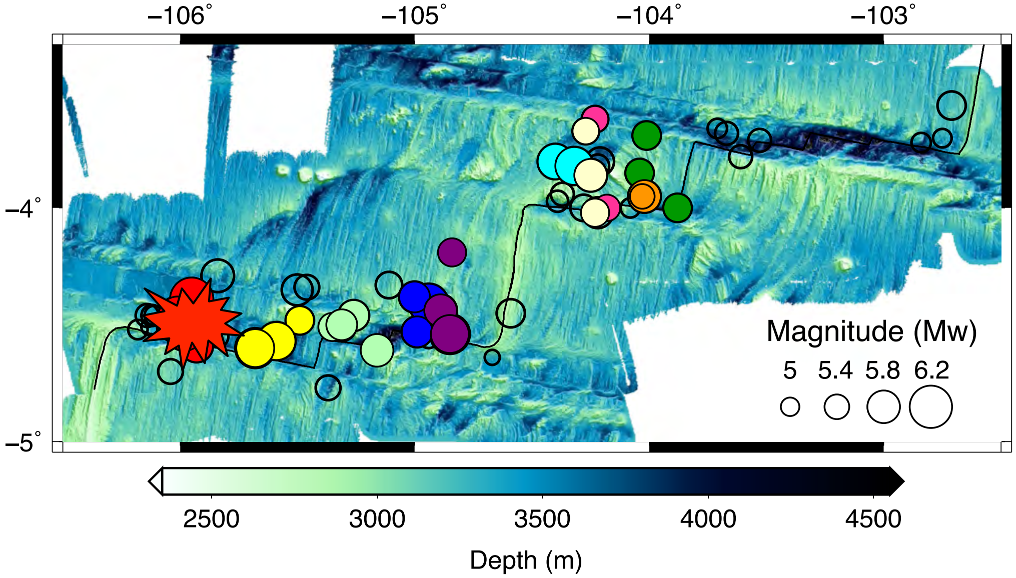


Long Term Predictability-Stable Seismic Cycles

McGuire, BSSA, 2008
Boettcher and McGuire, GRL, 2009
McGuire et al., Nature Geoscience, 2012

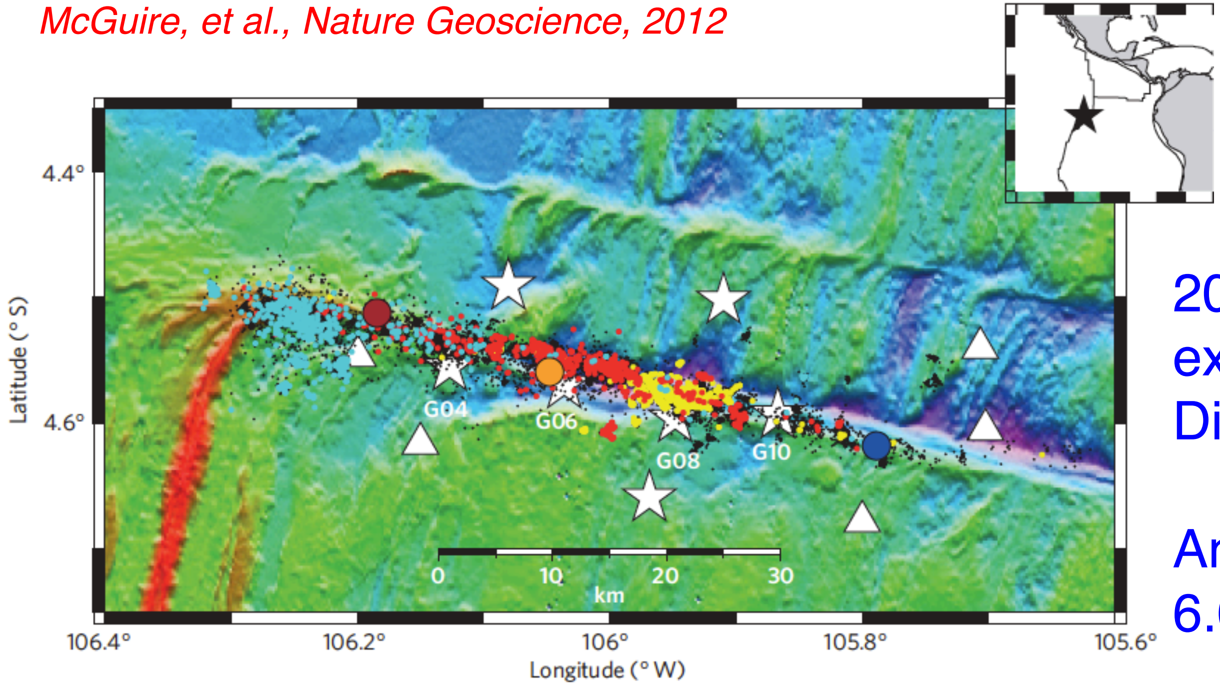
Fast slipping EPR faults have VERY short and stable seismic cycles!





Long Term Predictability- Stable Seismic Cycles

McGuire, et al., Nature Geoscience, 2012

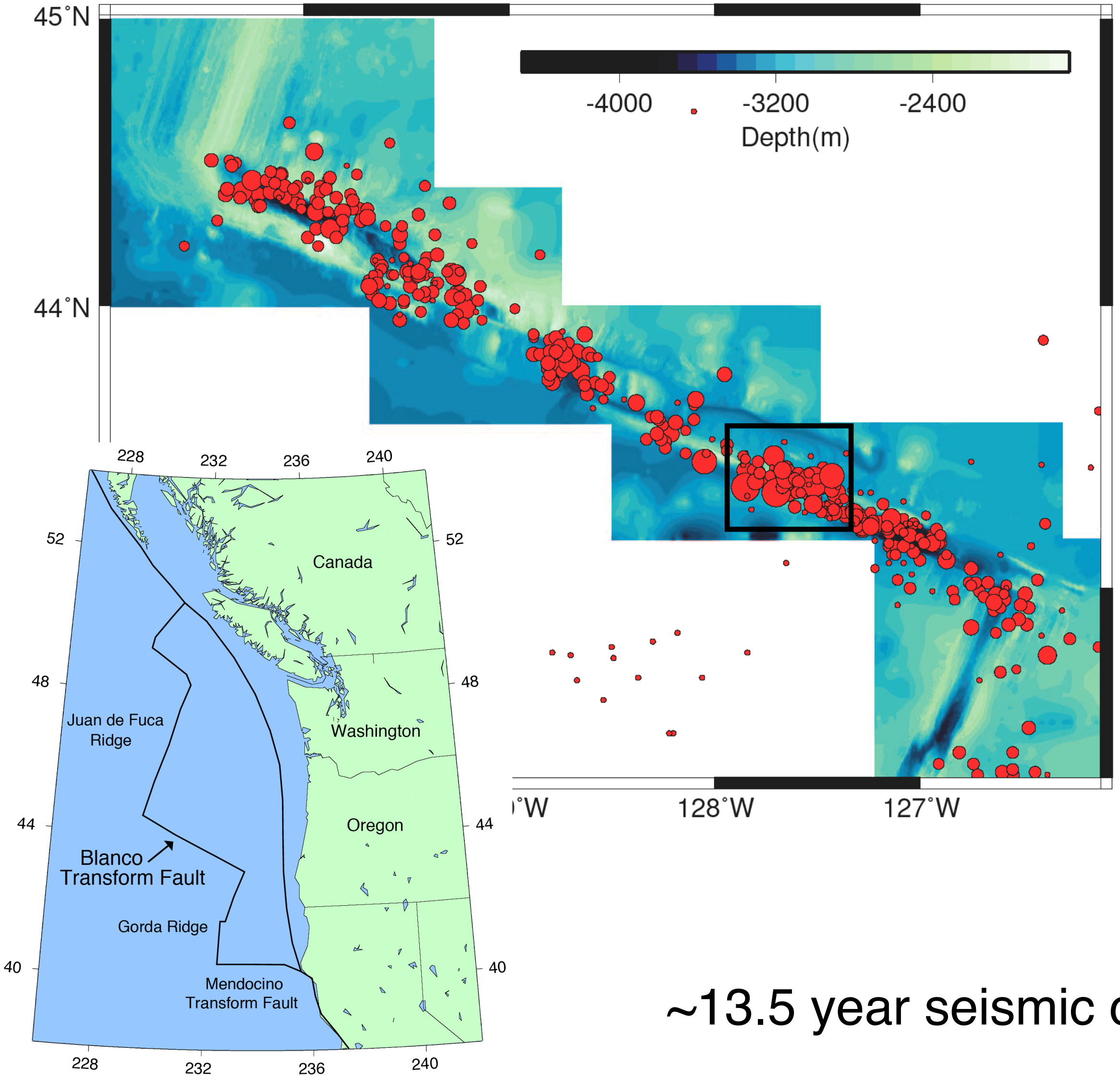


2008 Ocean Bottom Seismic experiment on Gofar, Discovery, & Quebrada

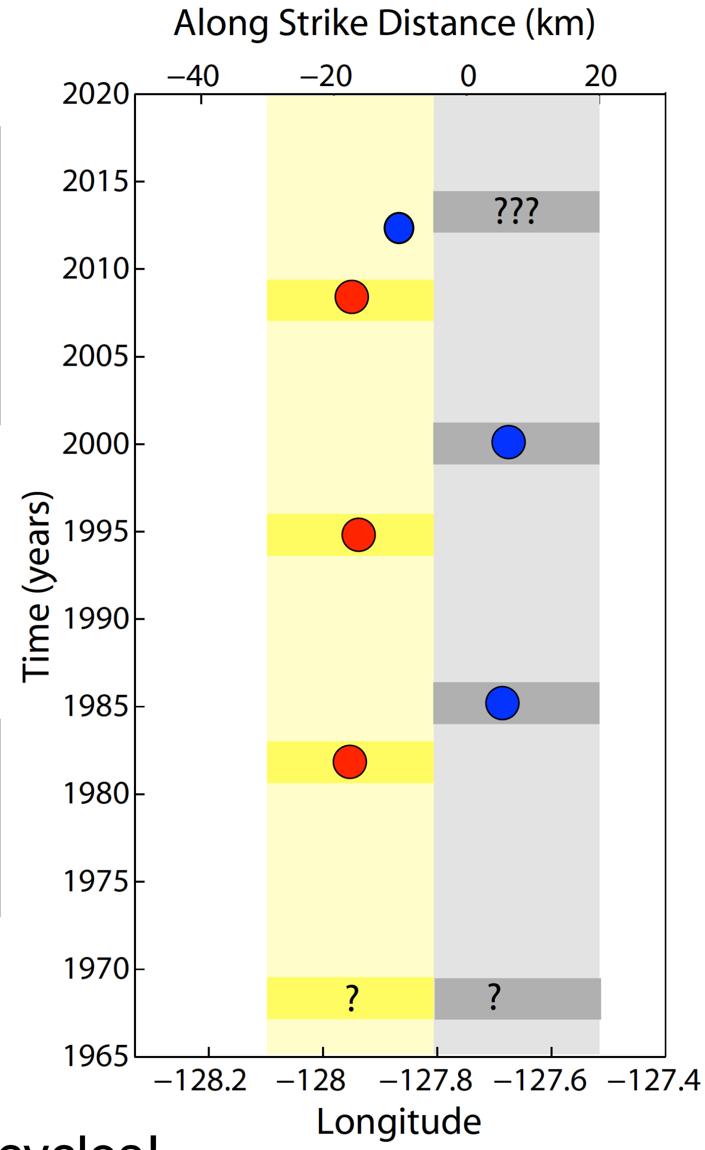
And the Sept. 18th, 2008 M_W 6.0 earthquake sequence!

Long Term Predictability- Stable Seismic Cycles

Boettcher and McGuire, GRL, 2009



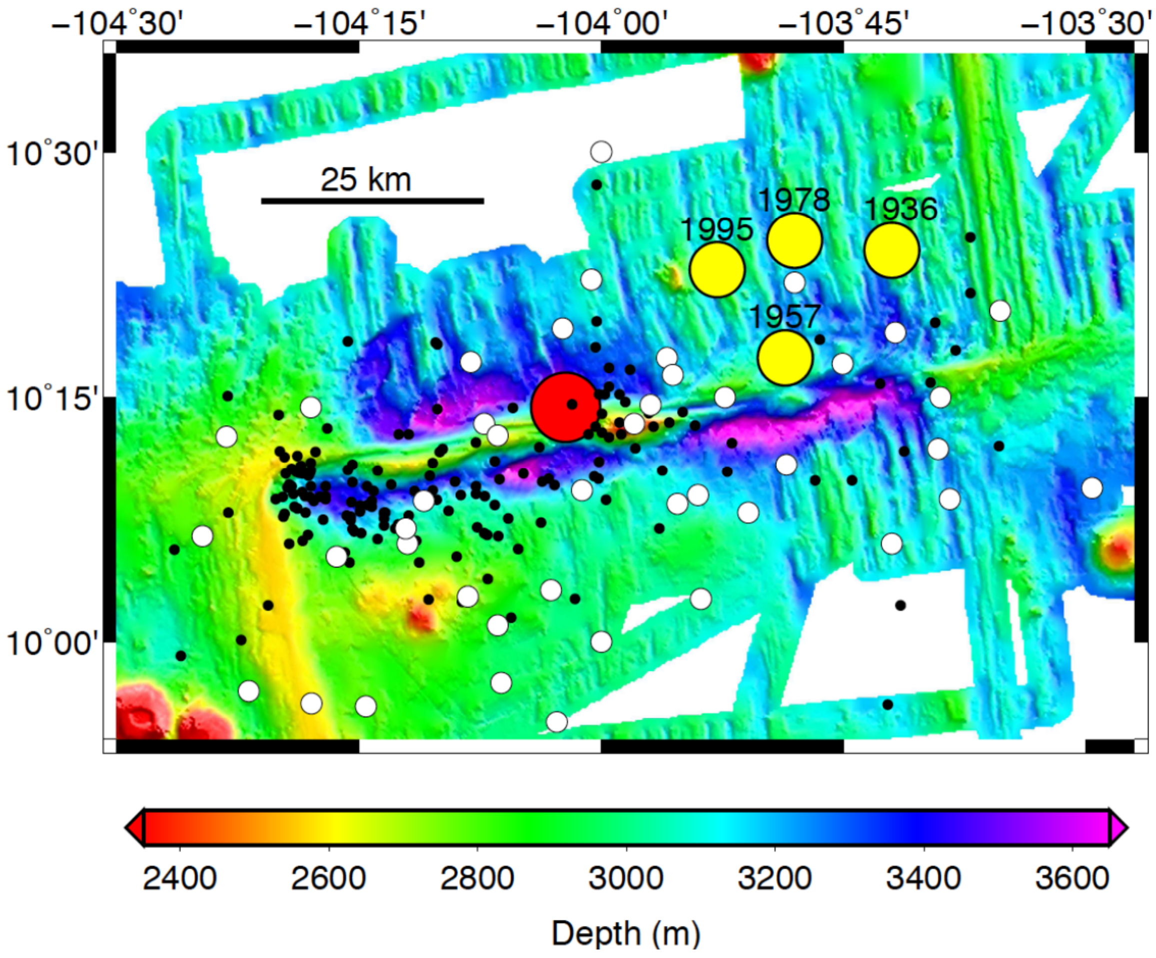
Blanco Transform Fault

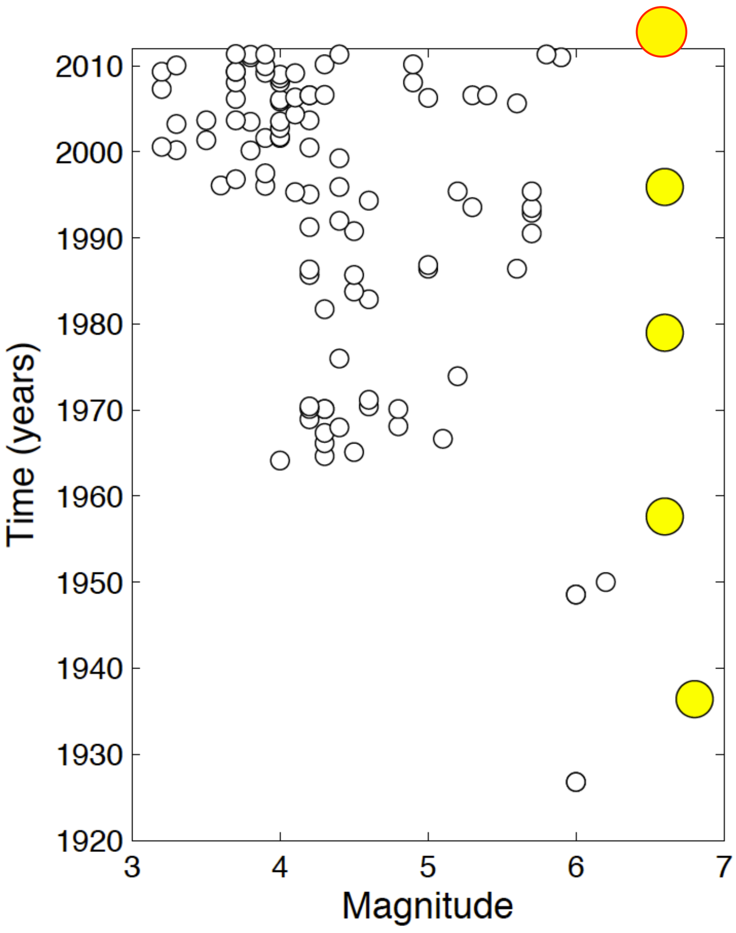


~13.5 year seismic cycles!

Long Term Predictability- Stable Seismic Cycles

Clipperton Transform Fault



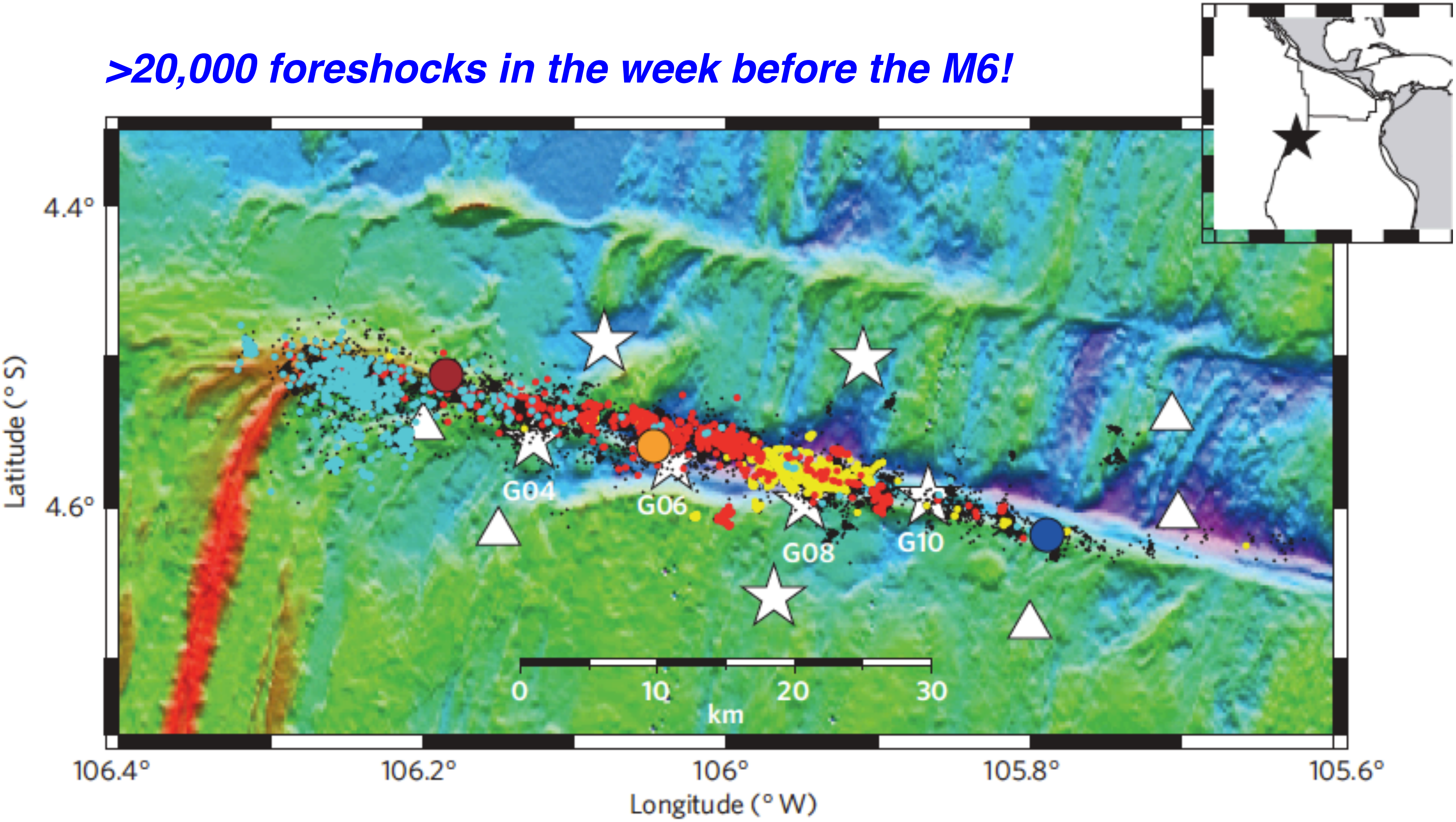


~20 year seismic cycles!

Short Term Earthquake Predictability- Foreshocks

McGuire, et al., Nature Geoscience, 2012

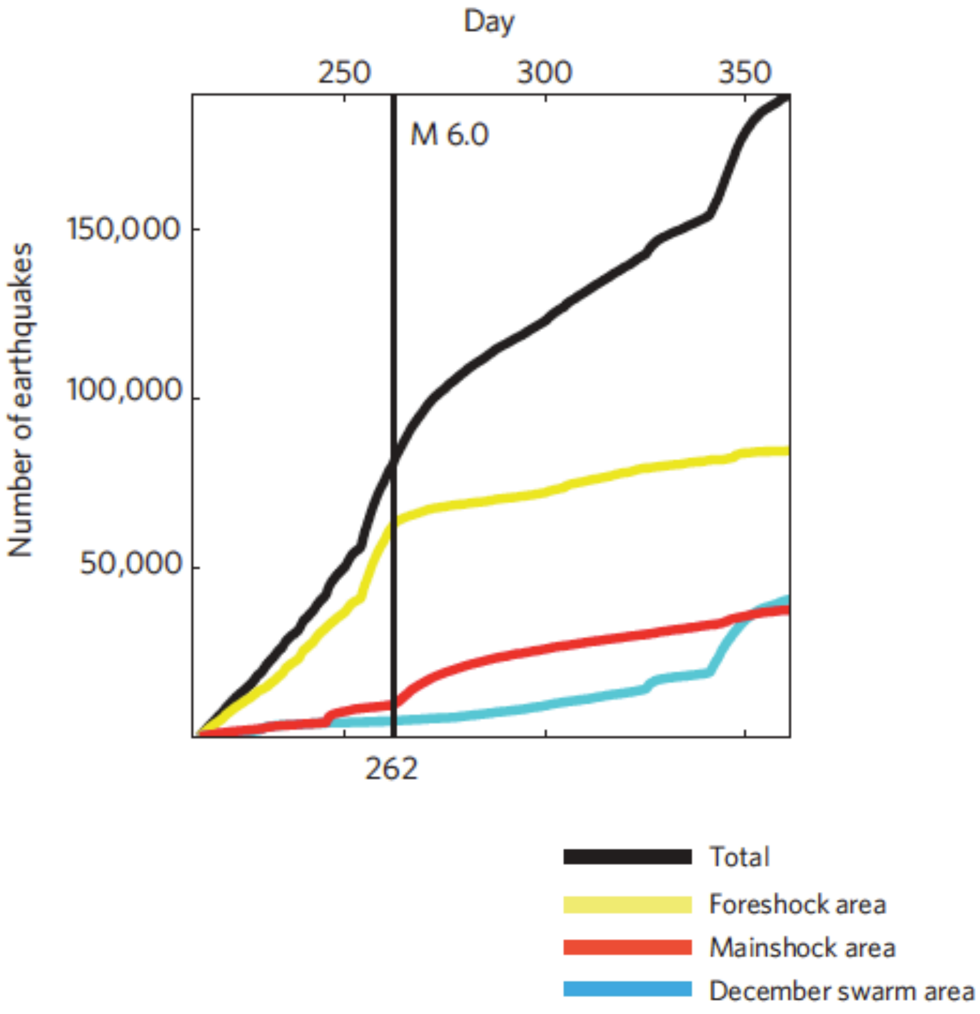
>20,000 foreshocks in the week before the M6!

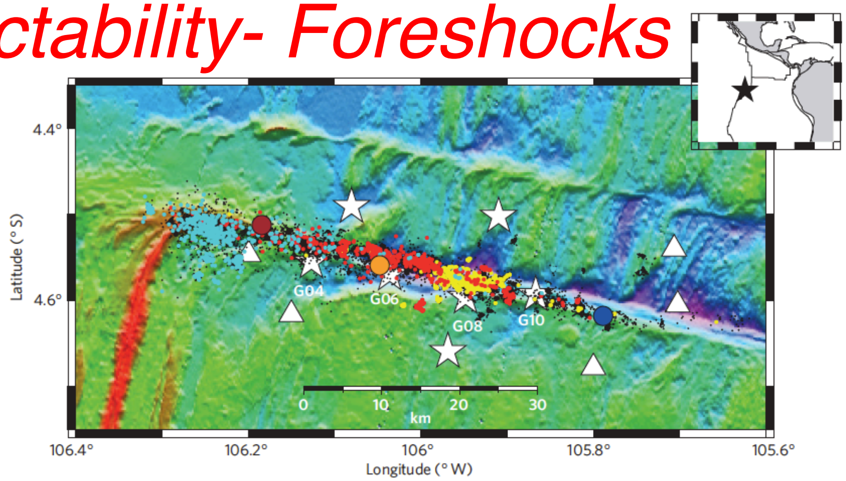


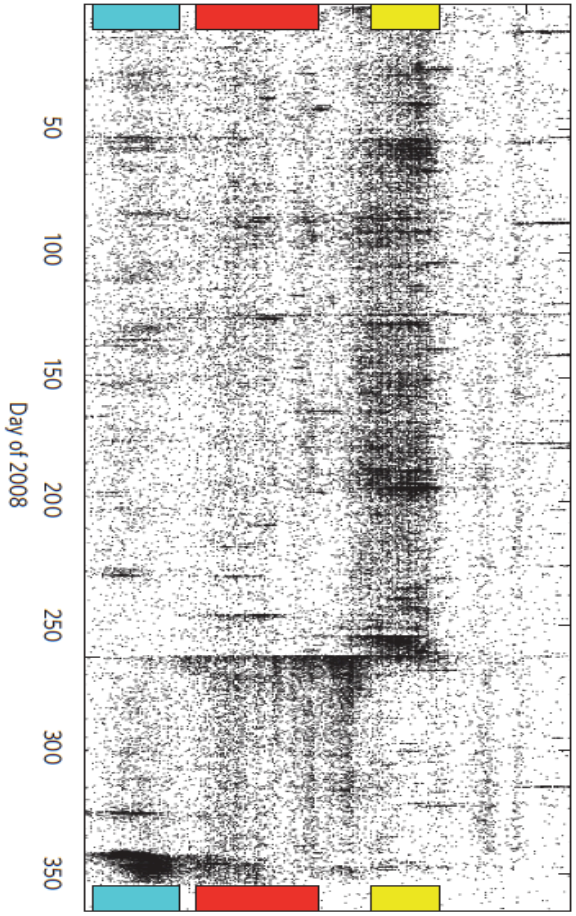
Short Term Earthquake Predictability- Foreshocks

McGuire, et al., Nature Geoscience, 2012

Foreshocks are abundant and localized!

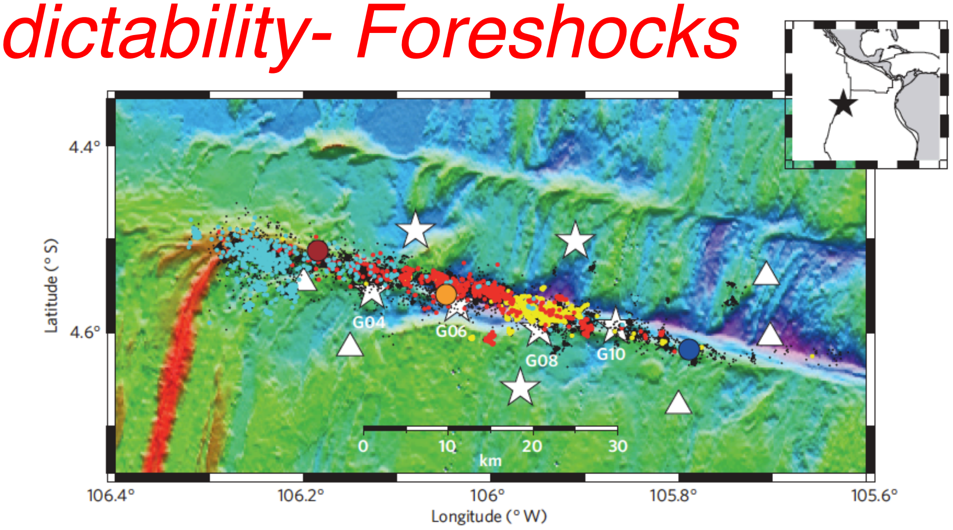




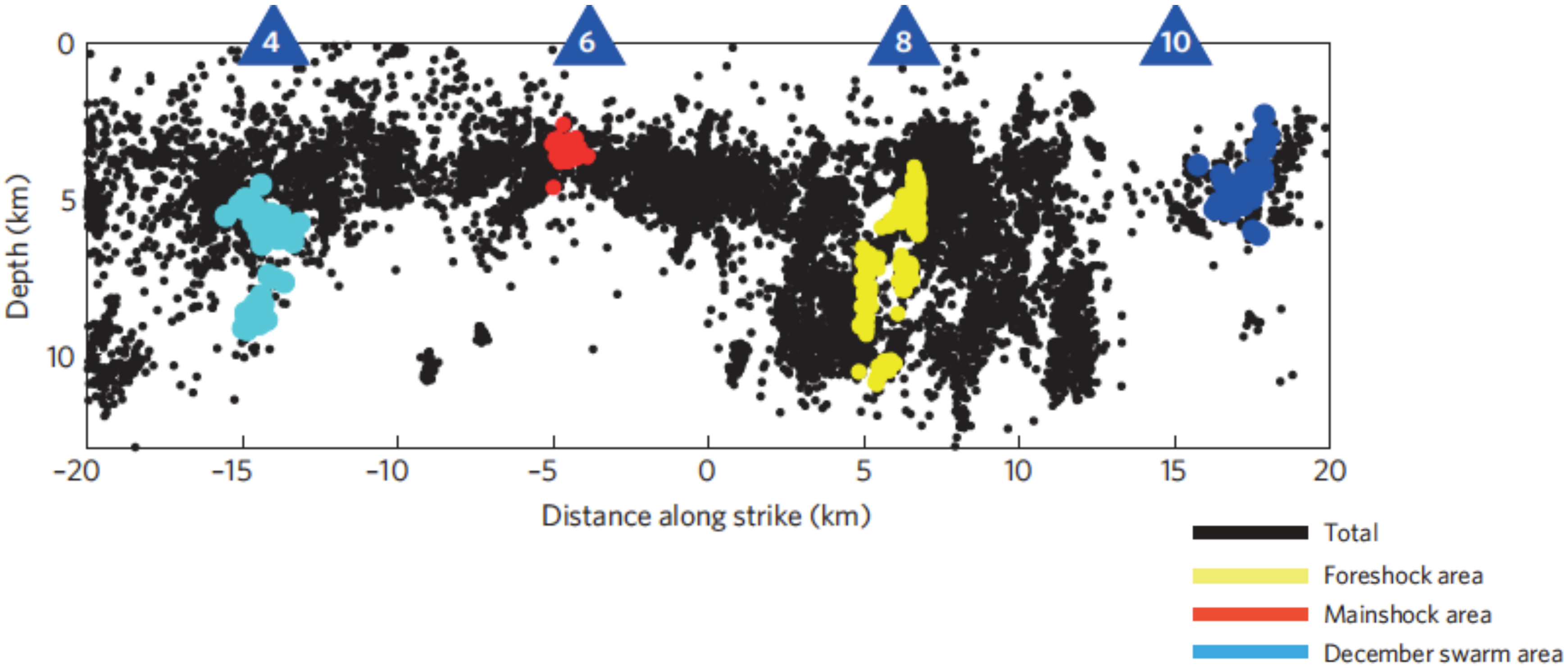


Short Term Earthquake Predictability- Foreshocks

McGuire, et al., Nature Geoscience, 2012

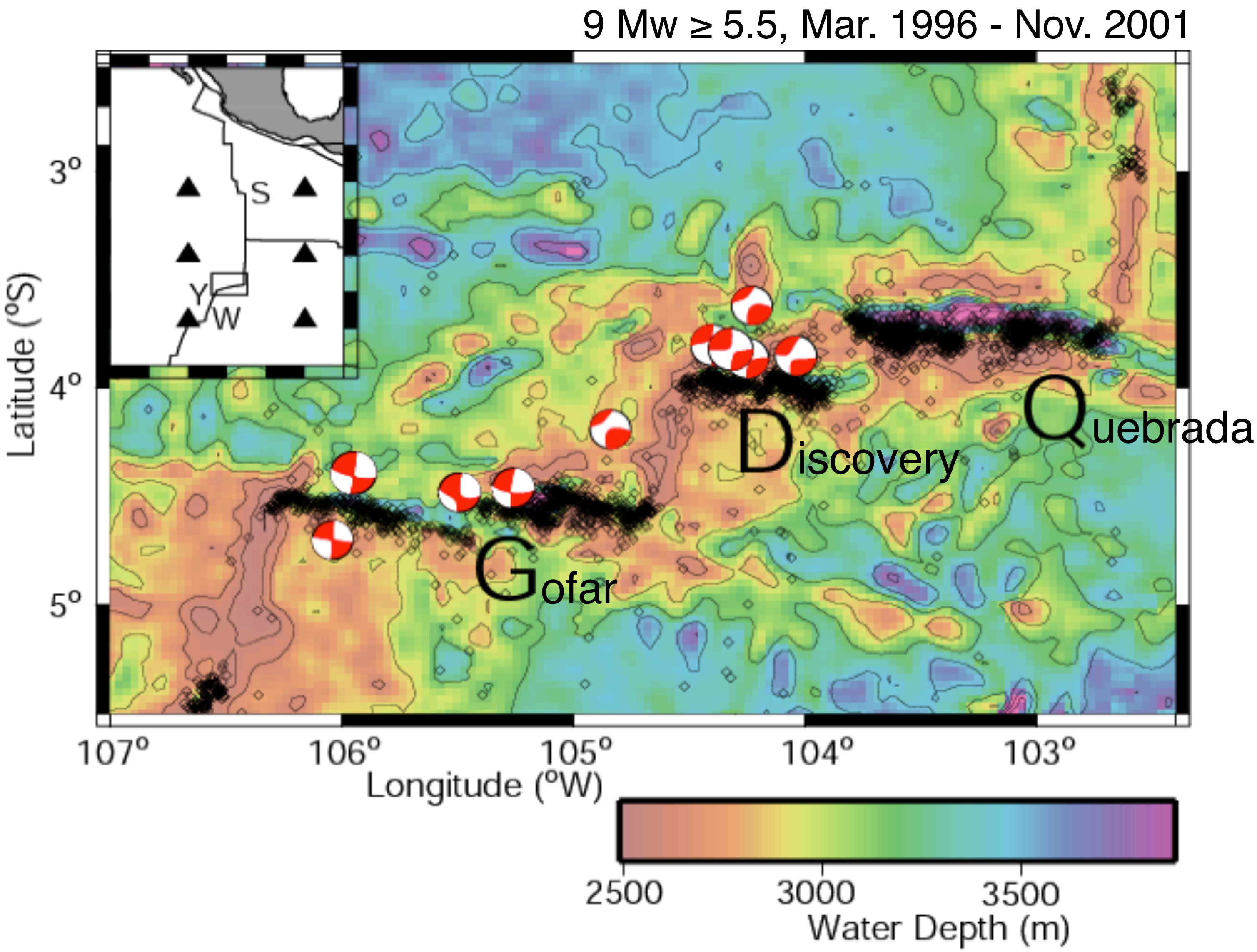


Foreshocks are deep!



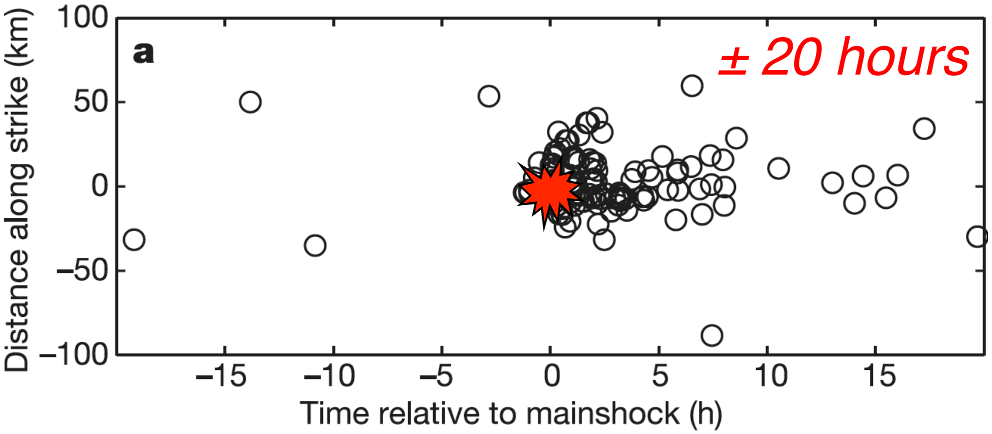
Short Term Earthquake Predictability- Foreshocks

McGuire, et al., Nature, 2005



Short Term Earthquake Predictability- Foreshocks

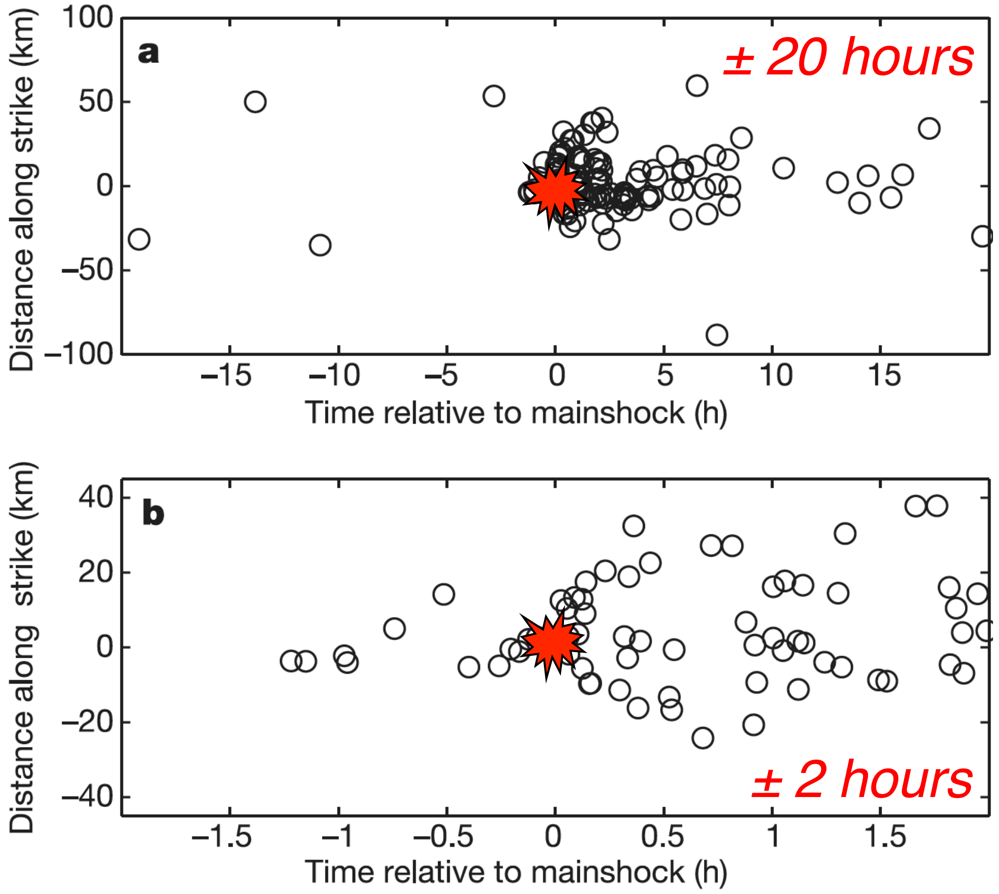
McGuire, et al., Nature, 2005



Stack of the 9 mainshocks

Short Term Earthquake Predictability- Foreshocks

McGuire, et al., Nature, 2005

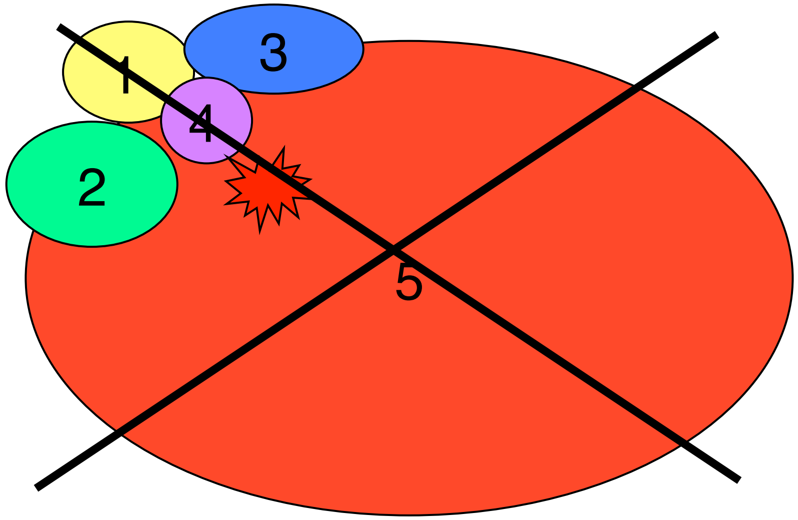


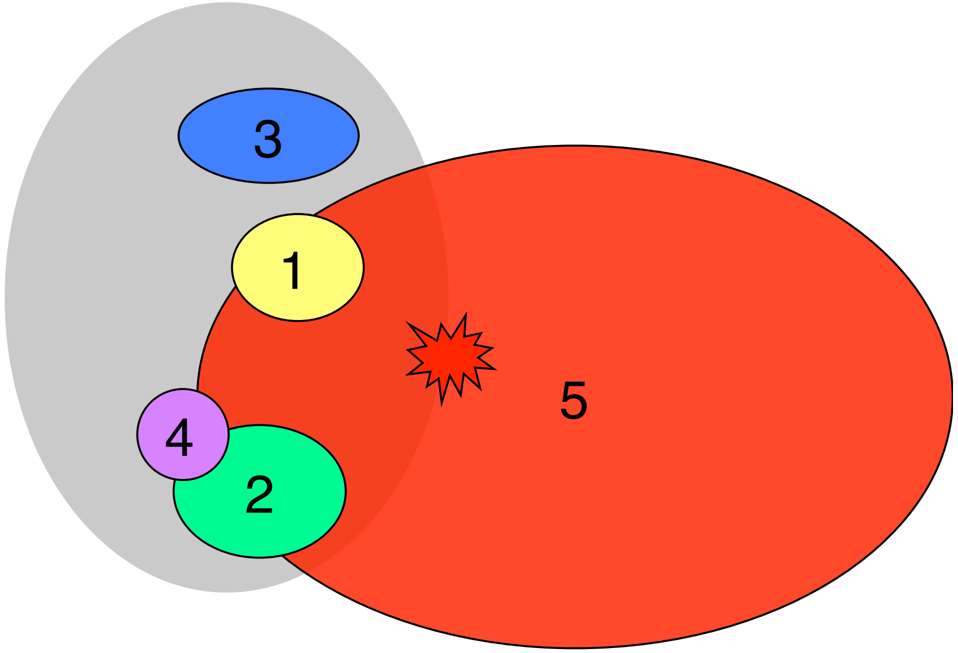
Stack of the 9 mainshocks

M ≥ 5.5 earthquakes on QDG are preceded by a foreshock within one hour and 15 km

Short Term Earthquake Predictability- Foreshocks

Are foreshocks, mainshocks, and aftershocks all triggered in the same way (e.g. ETAS)?

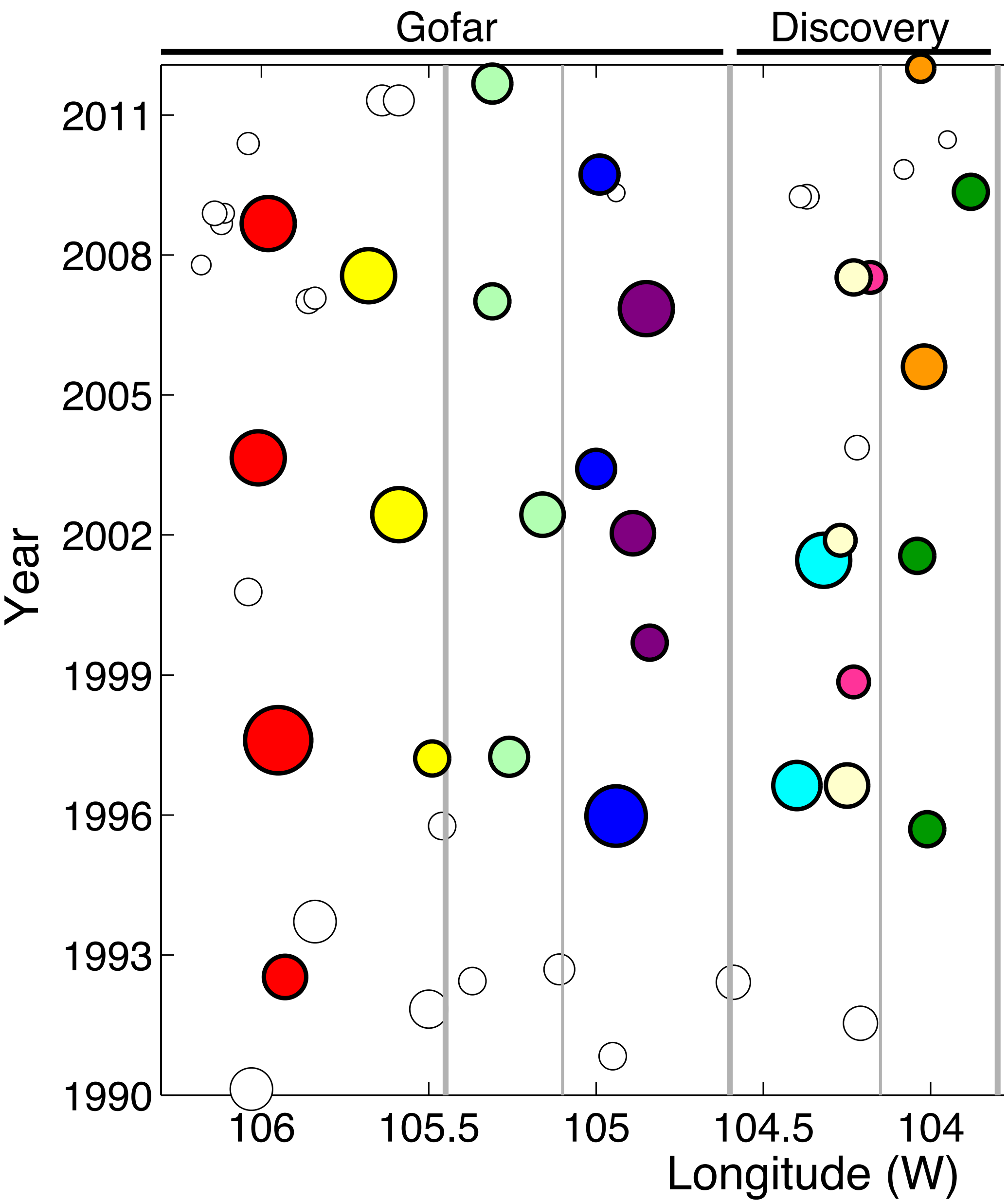




“Pre-Slip Model”

Observations of Seismic Cycles on Oceanic Transform Faults

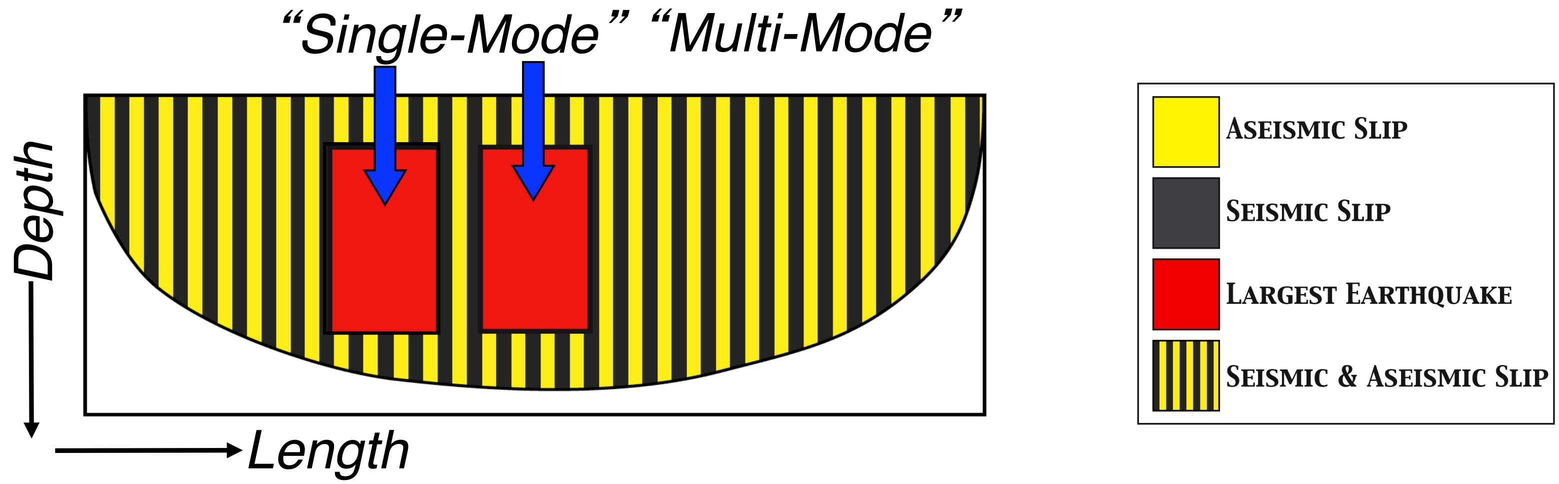
- Regular, Short (≥5 years) seismic cycles!
- Large events repeatedly re-rupture the same fault patch
- Ruptures don't rupture multiple patches, even within fault segments
- Foreshocks precede most(?) large earthquakes on fast slipping transform faults
- The size of these largest earthquakes are also predictable from the fault thermal area (L & V)



A model of slip on Ridge Transform Faults:

➔ *Single-mode fault patches separated by regions of multi-mode slip*

➔ *Fault zone frictional properties vary along strike, possibly due to high levels of fluid circulation in rupture barriers*



➔ *Creep may play an important role in driving seismic cycles on RTFs*