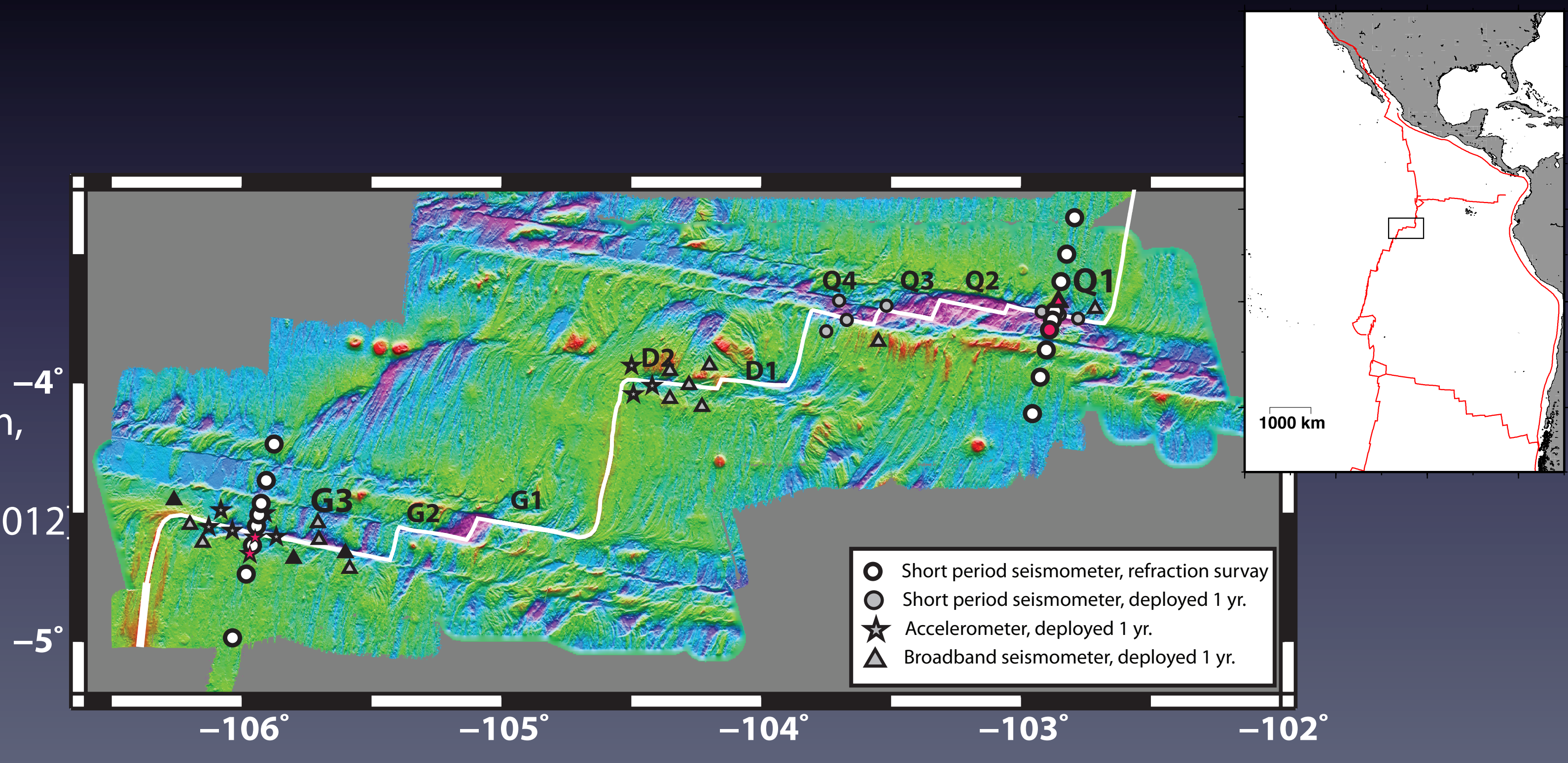
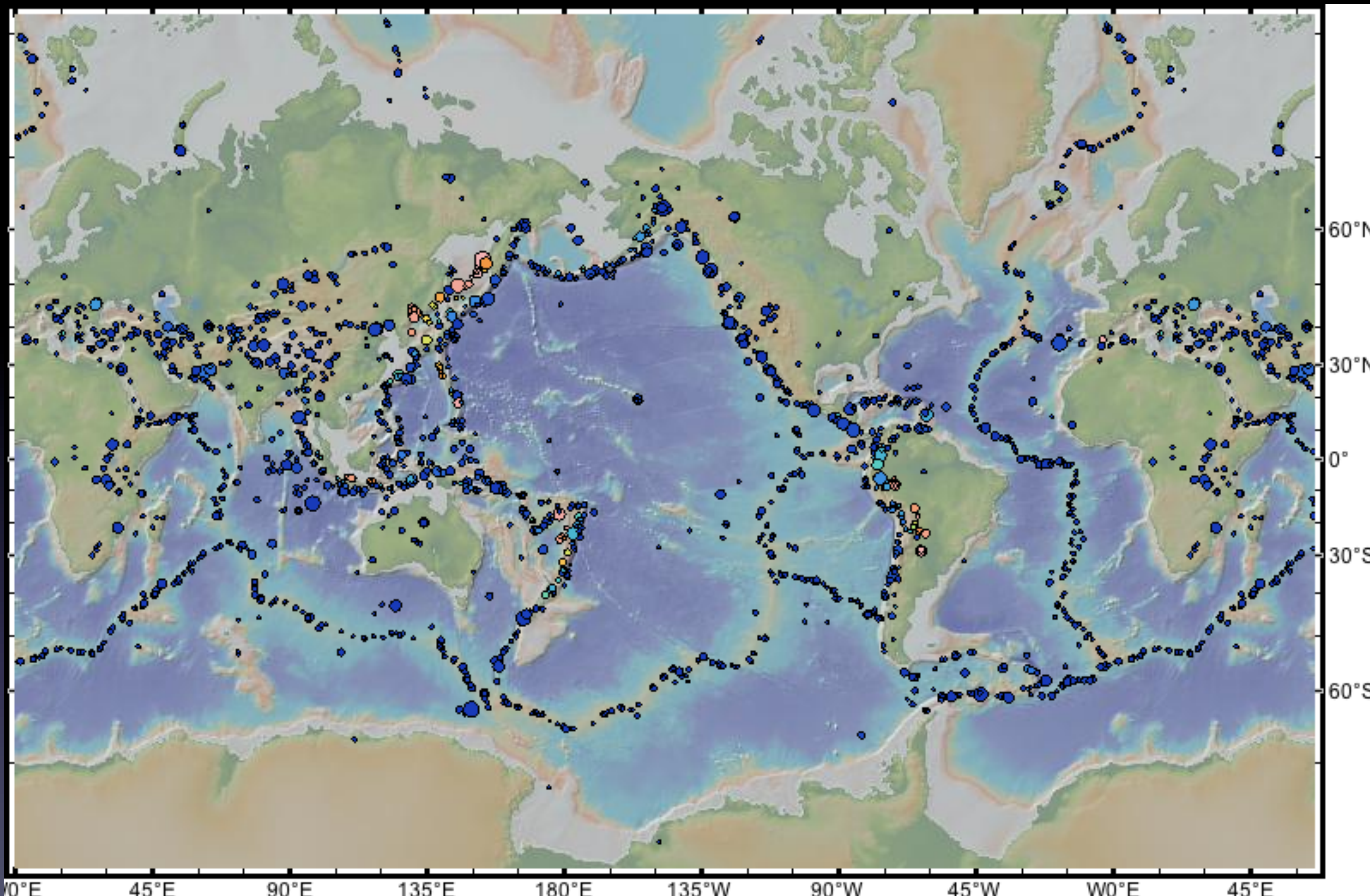
# Earthquakes on oceanic transform faults
## *Source scaling relations and rupture patterns*


**Yajing Liu (McGill)**

**Jeff McGuire, Mark Behn (WHOI)**

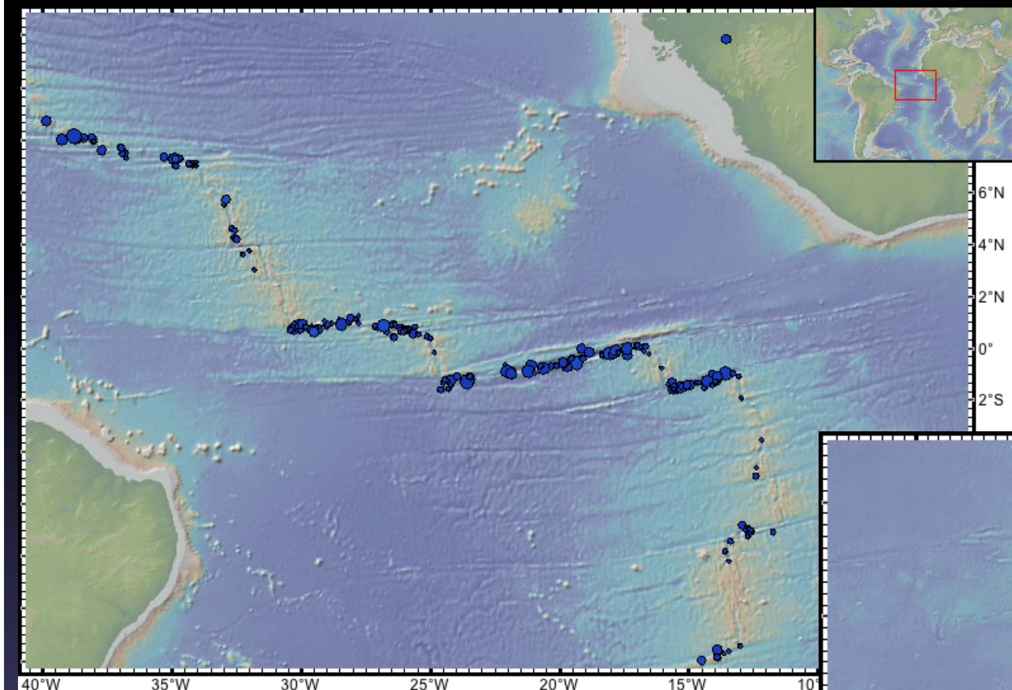

***Gofar***, *Discovery, Quebrada*, transform system, East Pacific Rise [McGuire et al., 2012]



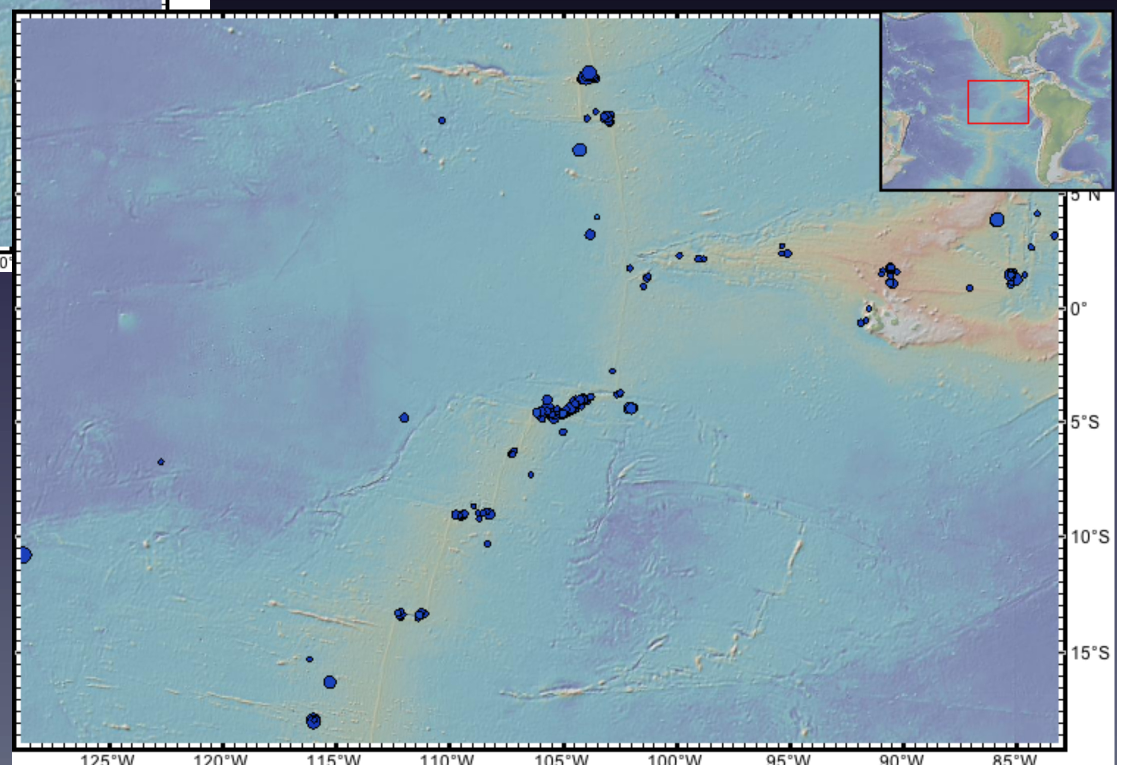



[seismicity, 1973-2013, M>5.5]

## Mid-Atlantic Ridge
## Slow spreading center



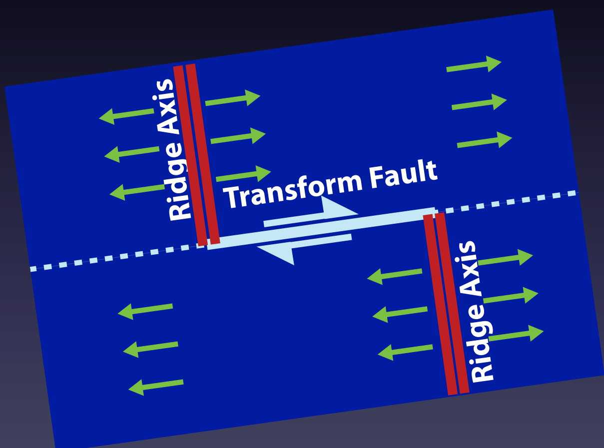

## East Pacific Rise
## Fast spreading center

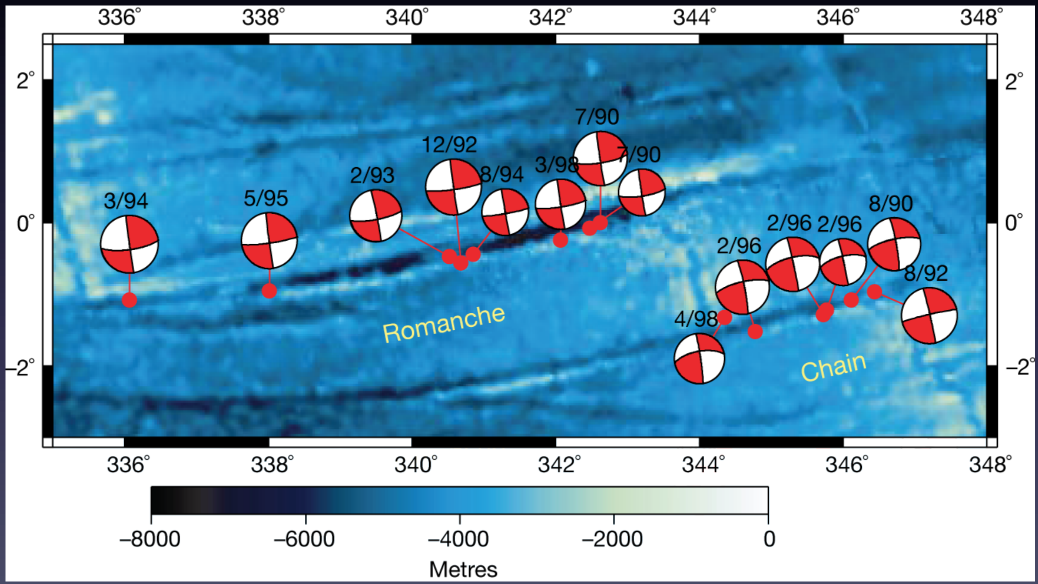


# Earthquakes on ocean transform faults

Compare to continental strike-slip faults:

- Relatively simple geometry



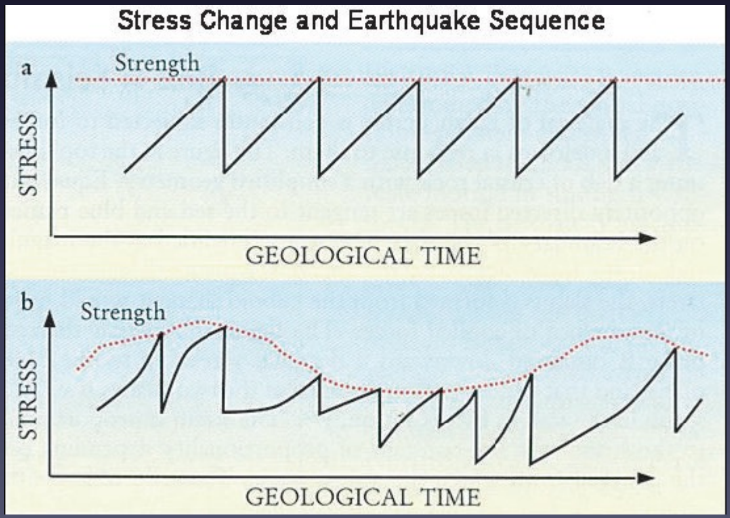




*[Abercrombie and Ekstrom, 2001]*

# Earthquakes on ocean transform faults

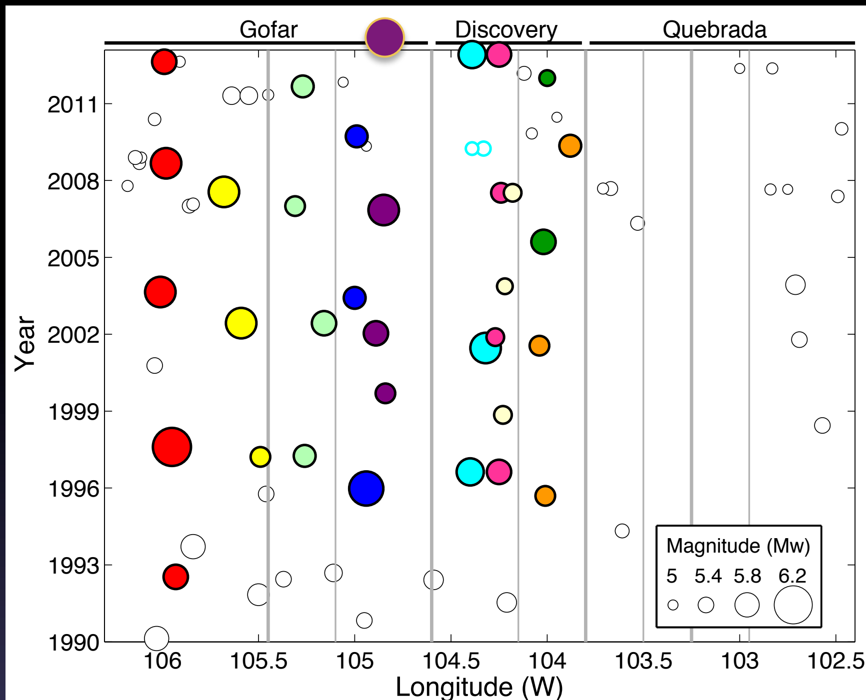
Compare to continental strike-slip faults:

- Relatively simple geometry
- Relatively simple and short seismic cycles (at least for those where multiple cycles have been observed)

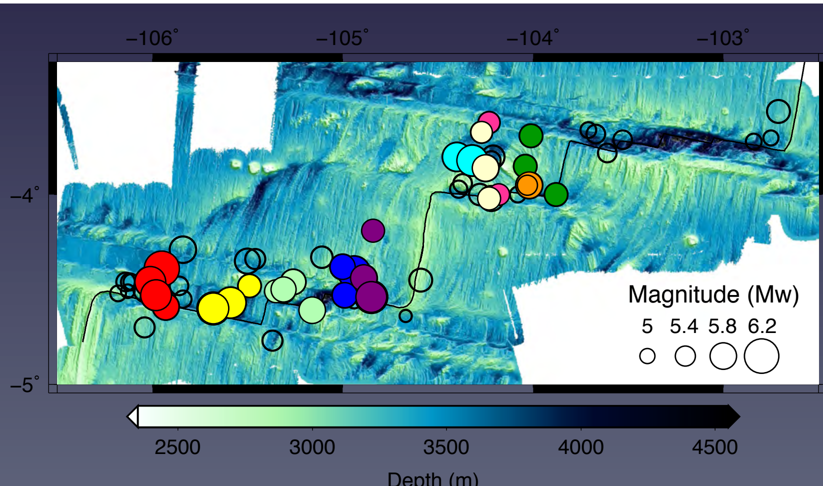


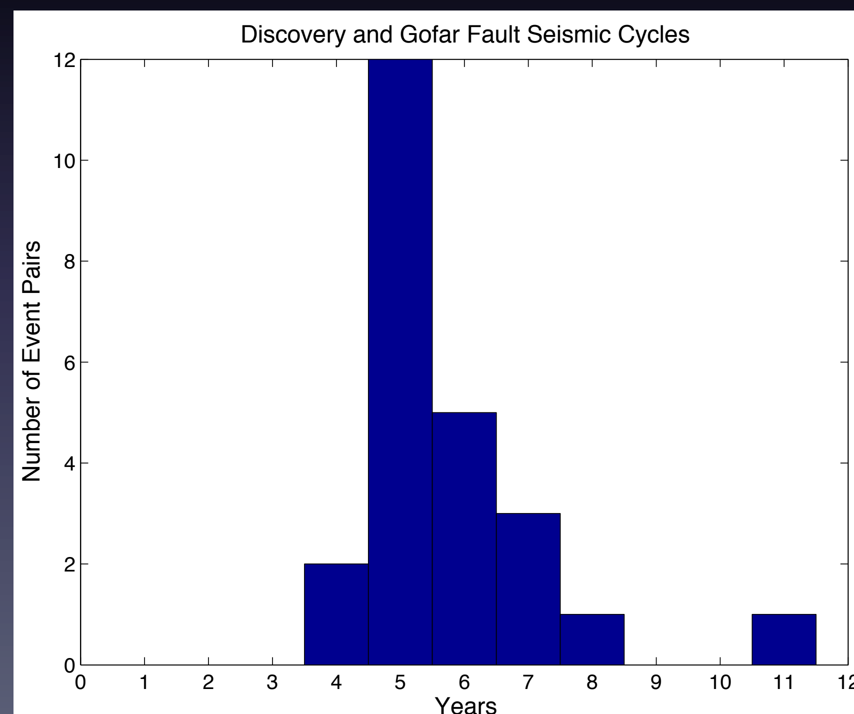

*[Kanamori and Brodsky, 2004]*

# Discovery and Gofar Transform Seismic Cycles




Mw 6 Ruptures repeat every ~5-6 years with indistinguishable centroids but seismic moments can vary by a factor of 2-3 between cycles. Overall, they are suggestive of fully coupled patches separated by creeping segments.




*[McGuire, 2008; updated by McGuire, 2014]*

# Earthquakes on ocean transform faults

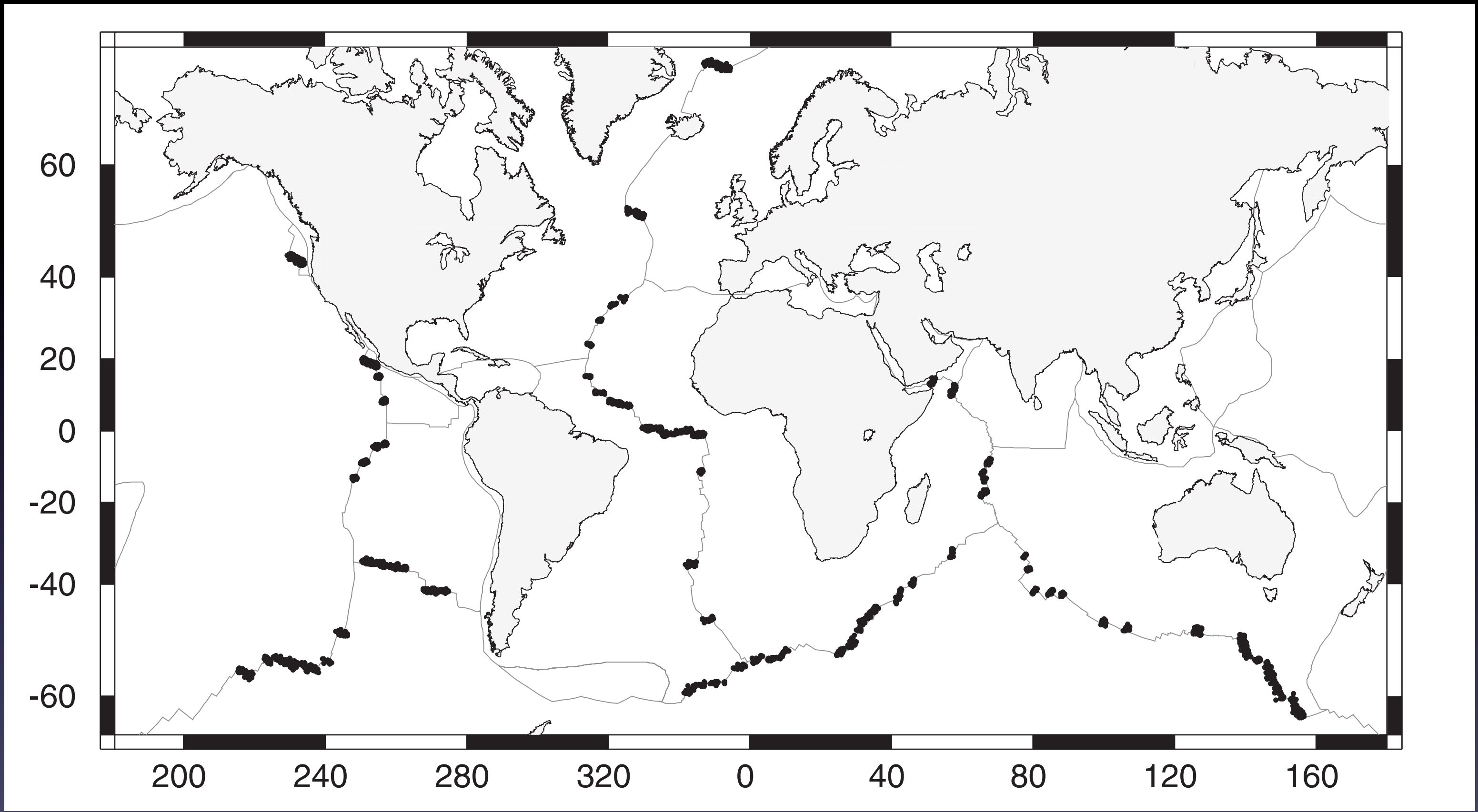
Compare to continental strike-slip faults:

- Relatively simple geometry
- Relatively simple seismic cycles (at least for those where multiple cycles have been observed)

- Remote locations, hard to access, sparse instrumentation

- *Abundant foreshocks but lower productivity of aftershocks [e.g., McGuire et al., 2005]*

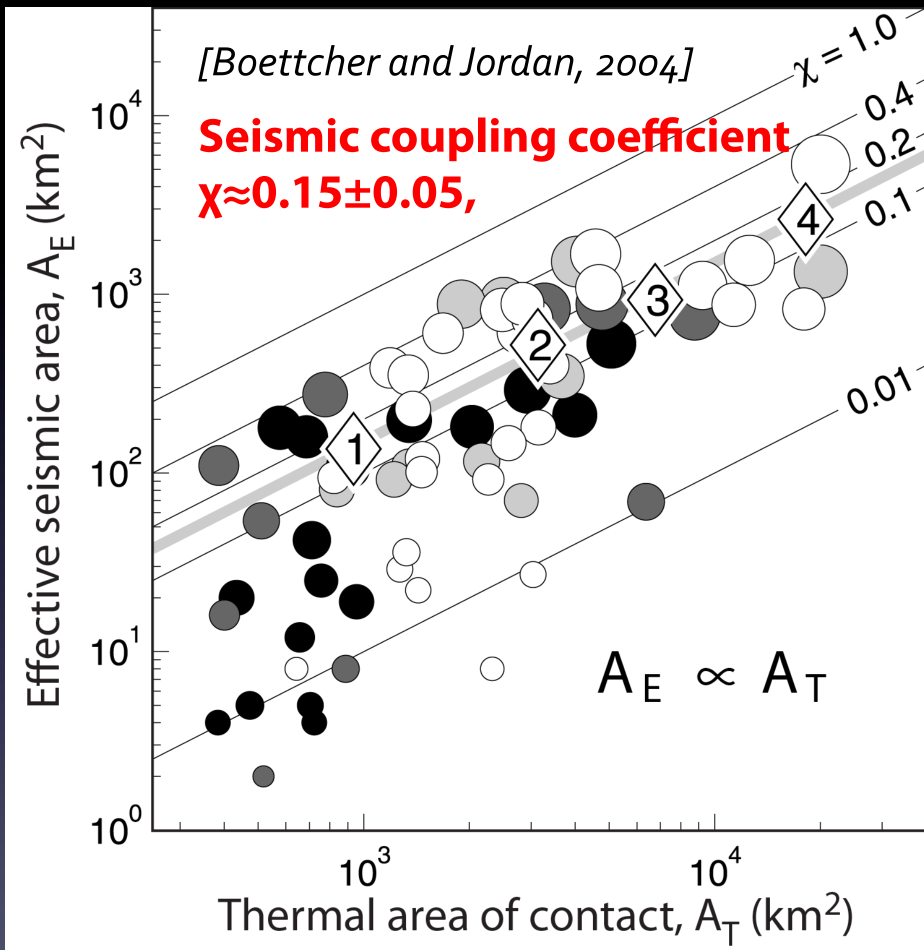
# Global distribution of 65 OTFs



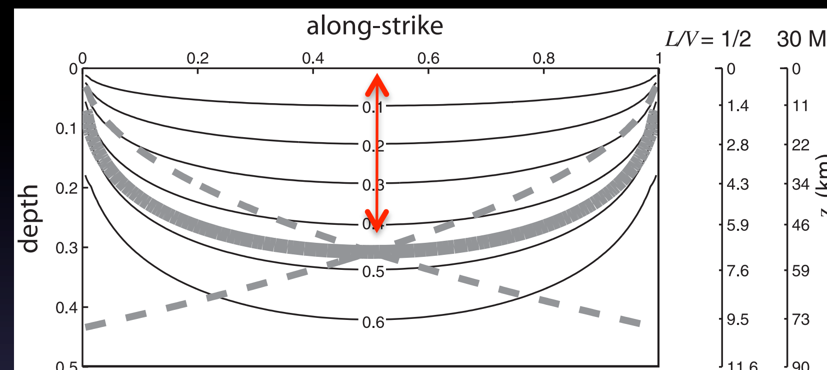

Total length 16,410 km
Seismicity catalogs: ISC 1964-1999; GCMT 1976-2002

*[Boettcher and Jordan, 2004]*

# OTF earthquake scaling relations (1)




**Thermal contact area $A_T$**: fault area above a reference isotherm (600ºC).



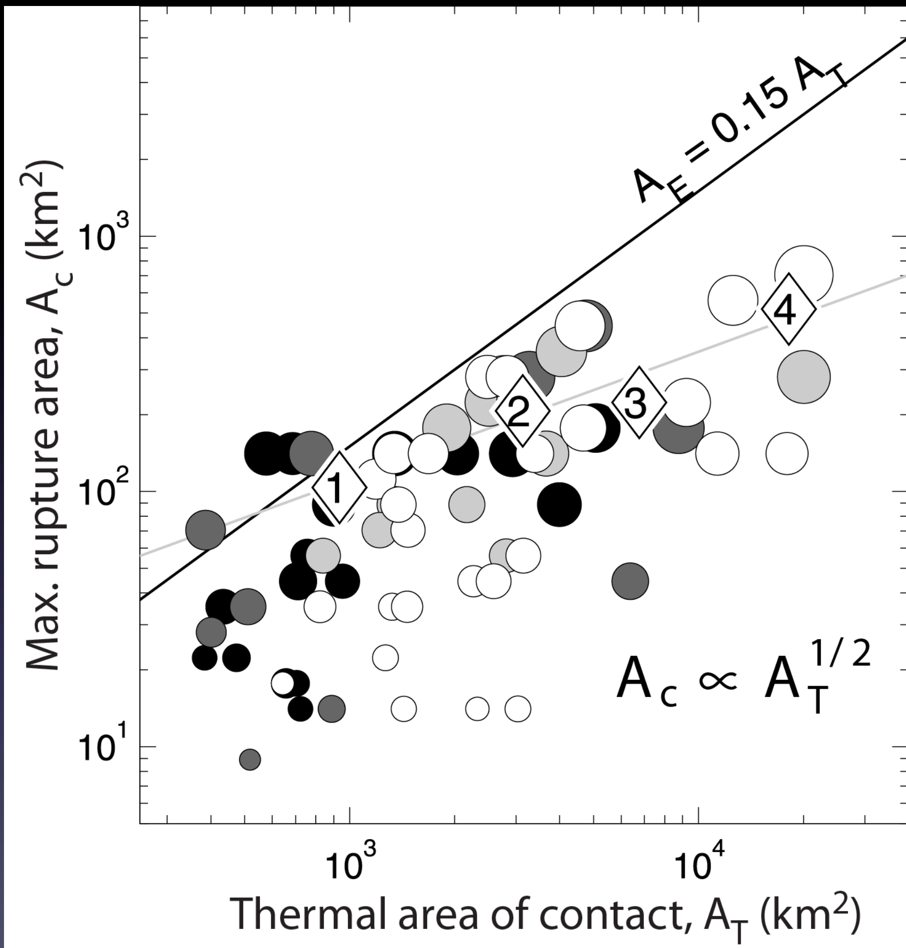

Half-space cooling thermal model

$$A_T \sim L^{3/2} / v^{1/2}$$

**Effective seismic area $A_E$**: total fault area that ruptures seismically averaged over many earthquake cycles.

$$A_E = \lim_{\Delta t \to \infty} \left( \sum M / \Delta t \right) / (\mu V_{pl})$$

# OTF earthquake scaling relations (2)




- **Cutoff (max.) rupture area $A_c$**: rupture area of the largest earthquake on an OTF, , assuming:
  - Constant stress drop $\Delta\tau = 3$ MPa
  - Slip $\delta = (\Delta\tau / \mu)\sqrt{A_C}$

$$A_C = (M_C / \Delta\tau)^{2/3}$$

**On average, larger OTFs have bigger earthquakes but smaller seismic productivities.**

**Largest EQ on OTFs**: Mw=7.1, March 1994
Rupture only propagates for ~ 120 km along the strike, despite a total fault length of 900 km.

# Earthquake frequency-size (G-R) distribution is well predicted

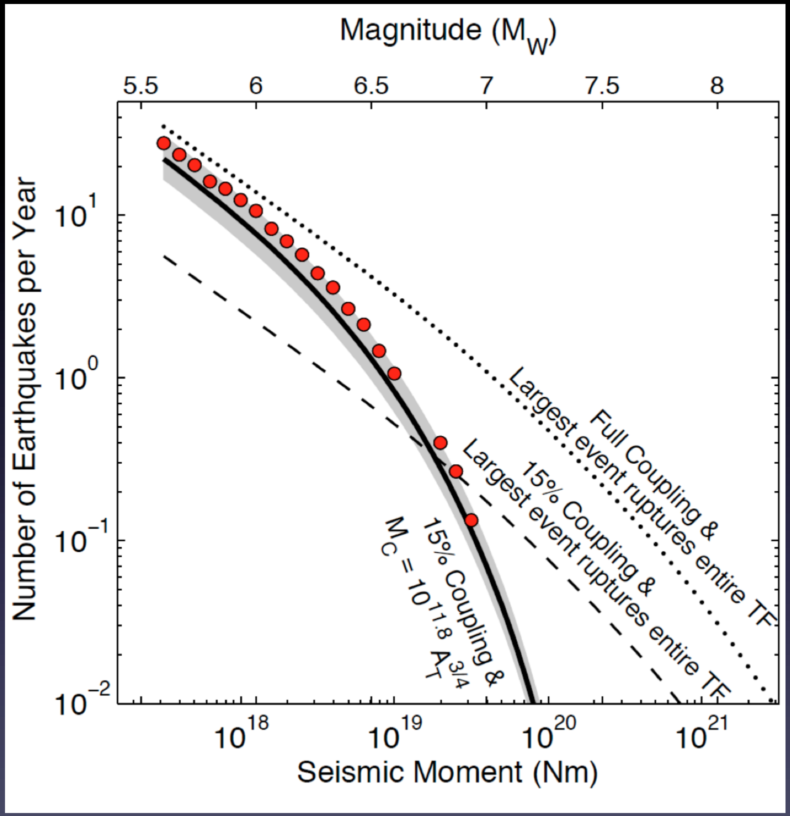
$$M_C = A_C^{3/2} / \Delta\tau = C A_T^{3/4} \quad (A_c \sim A_T^{1/2})$$

$$A_T \sim L z_{\max} = C_T L^{3/2} / v^{1/2}$$

(half-space cooling)

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

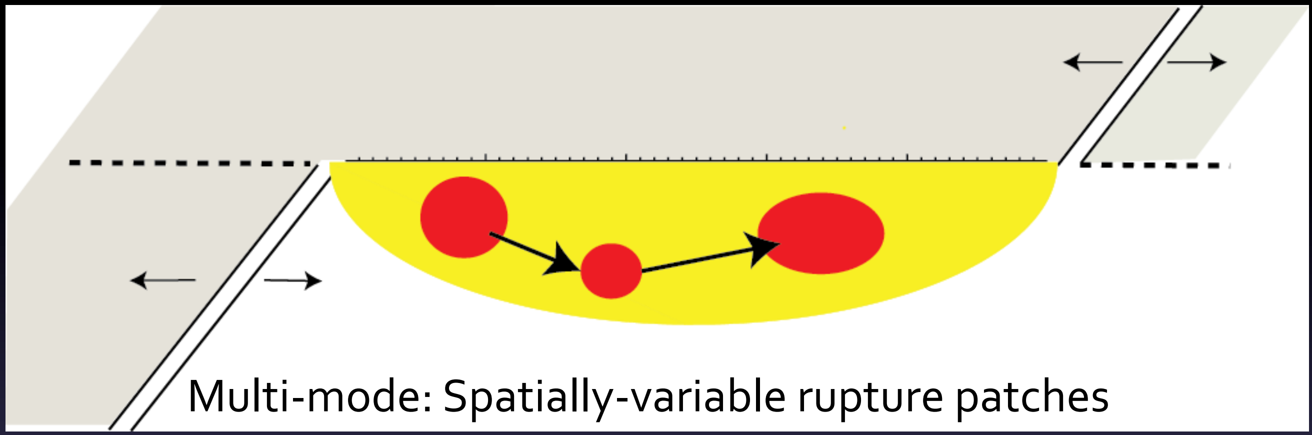
(tapered G-R relation)

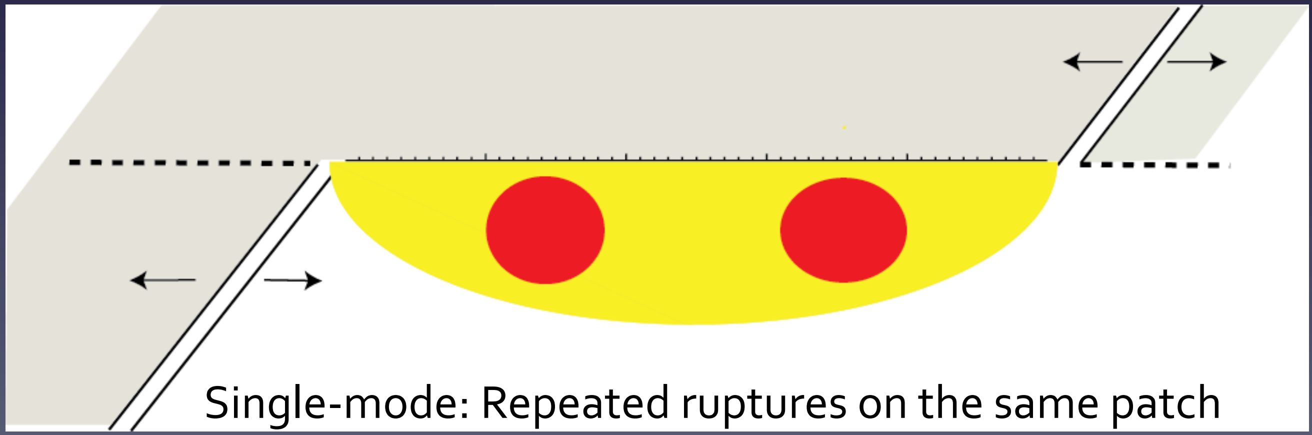



Estimate of C from 1964-2001 predicts 2002-2009 data extremely well.

[Boettcher and McGuire, 2009]

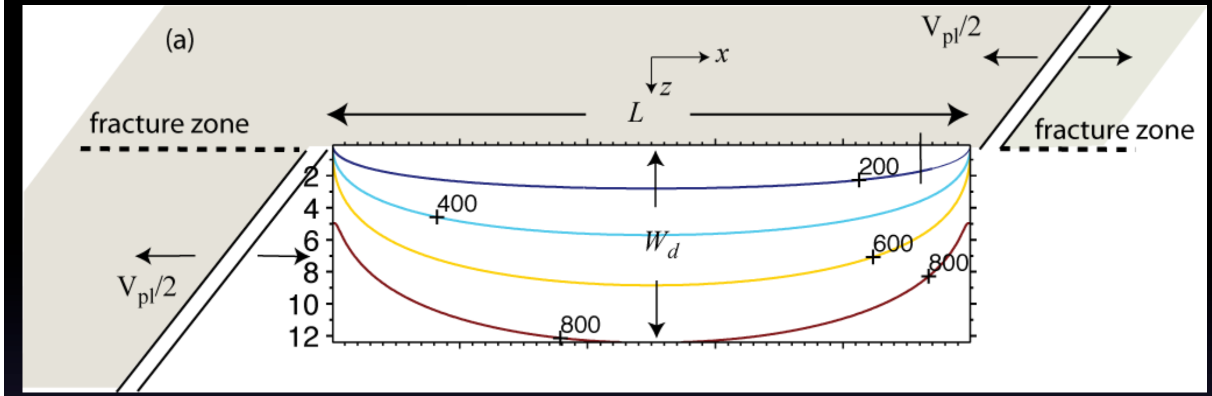
# “Multi-mode” vs “single-mode” seismogenic zone



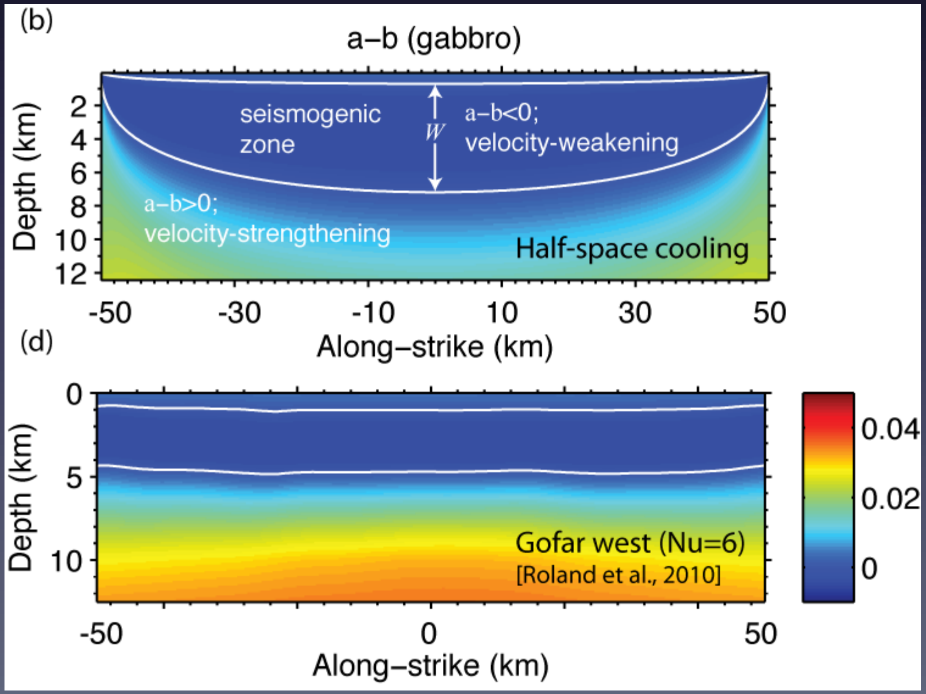




[conceptual model based on Boettcher and Jordan, 2004]

# Modeling OTF earthquake sequences




*[Liu et al., 2012]*




2D planar strike-slip fault embedded in 3D elastic medium.

Adjacent fracture zones modeled as extensions of the OTF.

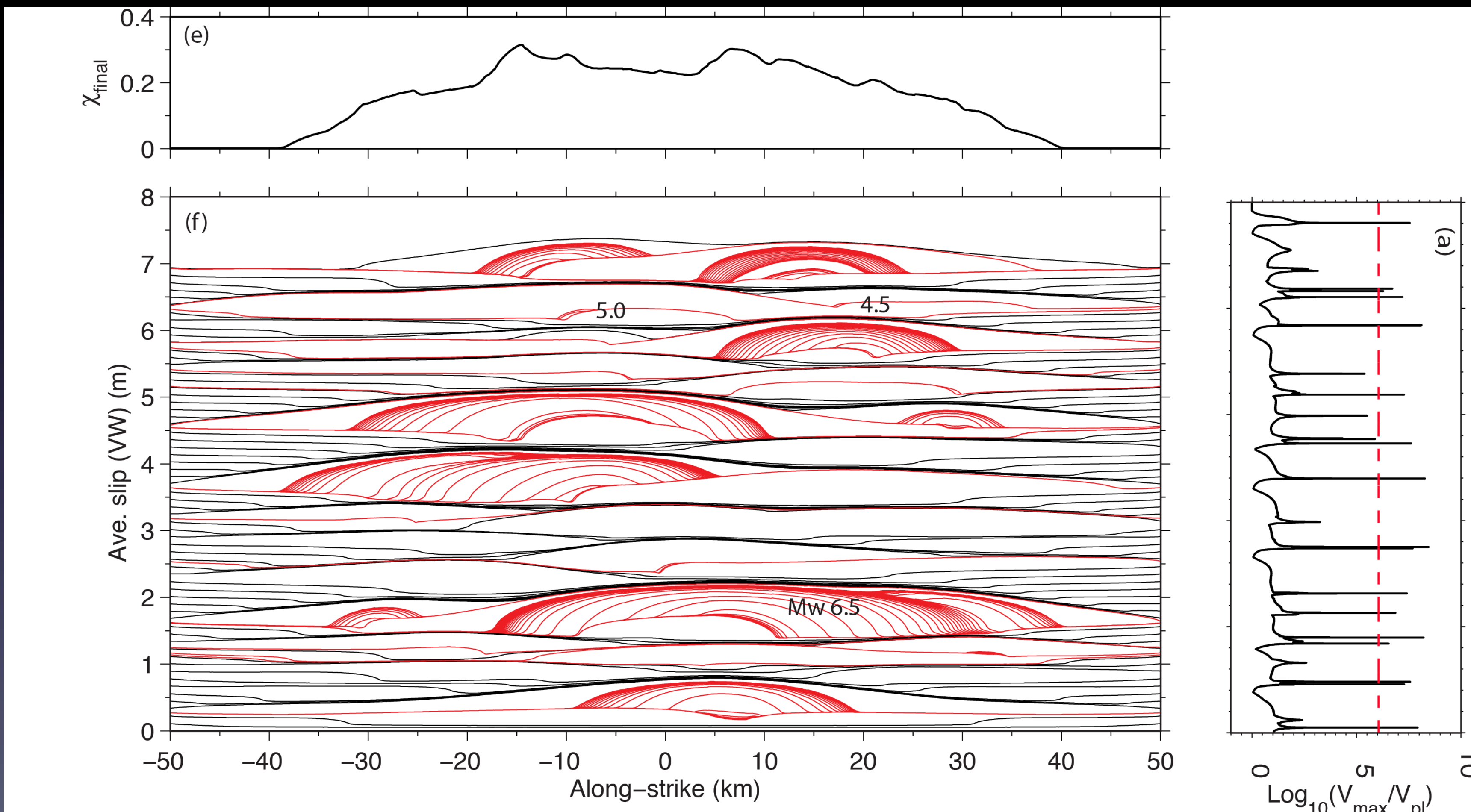
Entire domain (OTF + FZ) is repeated along-strike (FFT) [Rice, 1993; Lapusta et al., 2000]

- Rate-state frictional properties (gabbro + 2 OTF thermal models) [*He et al., 2007*]
- Instabilities (i.e., earthquakes) develop when the VW region is larger than a critical nucleation size [Rice and Ruina, 1983; *Rubin and Ampuero, 2005*].

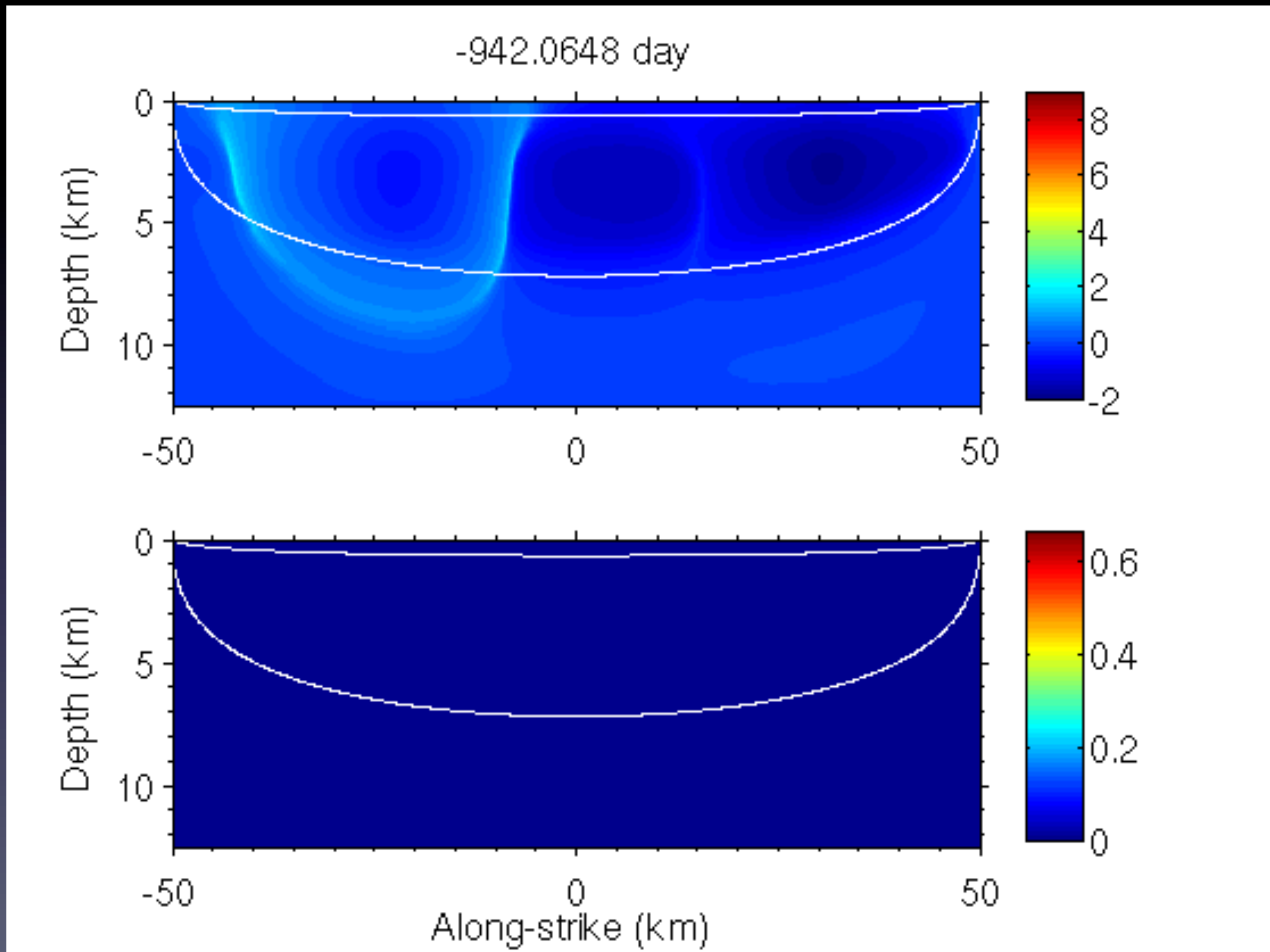
$$h^* = h^*_{RA} = \frac{2}{\pi} \frac{\mu b d_c}{(b-a)^2 \sigma}$$

# Short, fast spreading ridge OTF

*L = 100 km*, $V_{pl}$ *= 140 mm/yr, W/h**=1.63. $\chi_{final}$=0.17

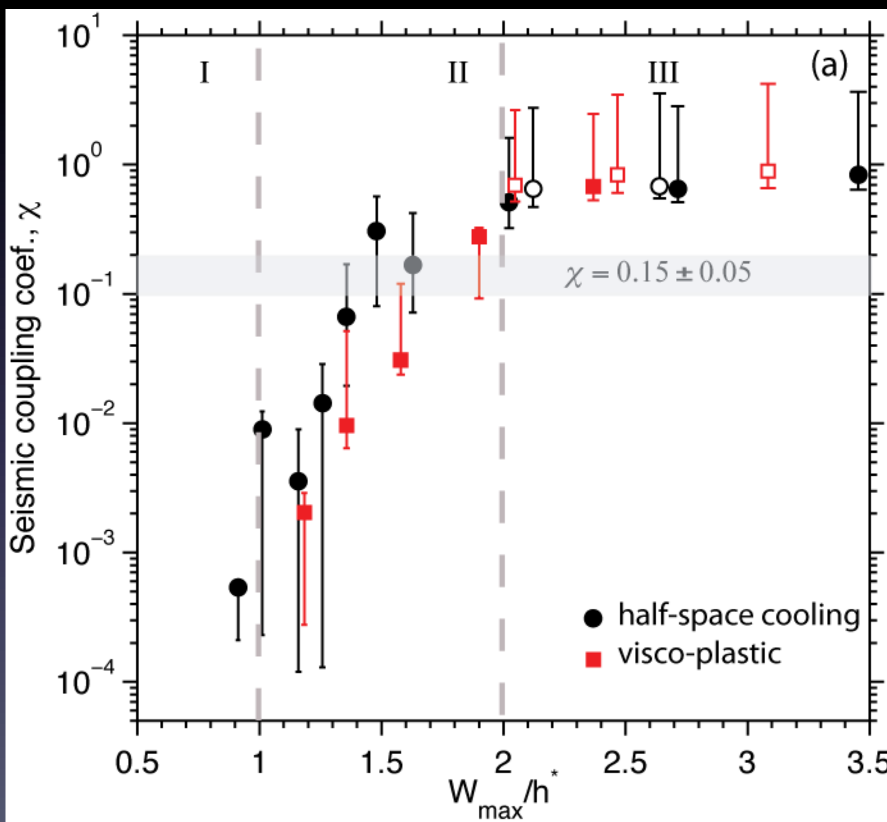


# Earthquake emerges as a coalesce of creeping fronts

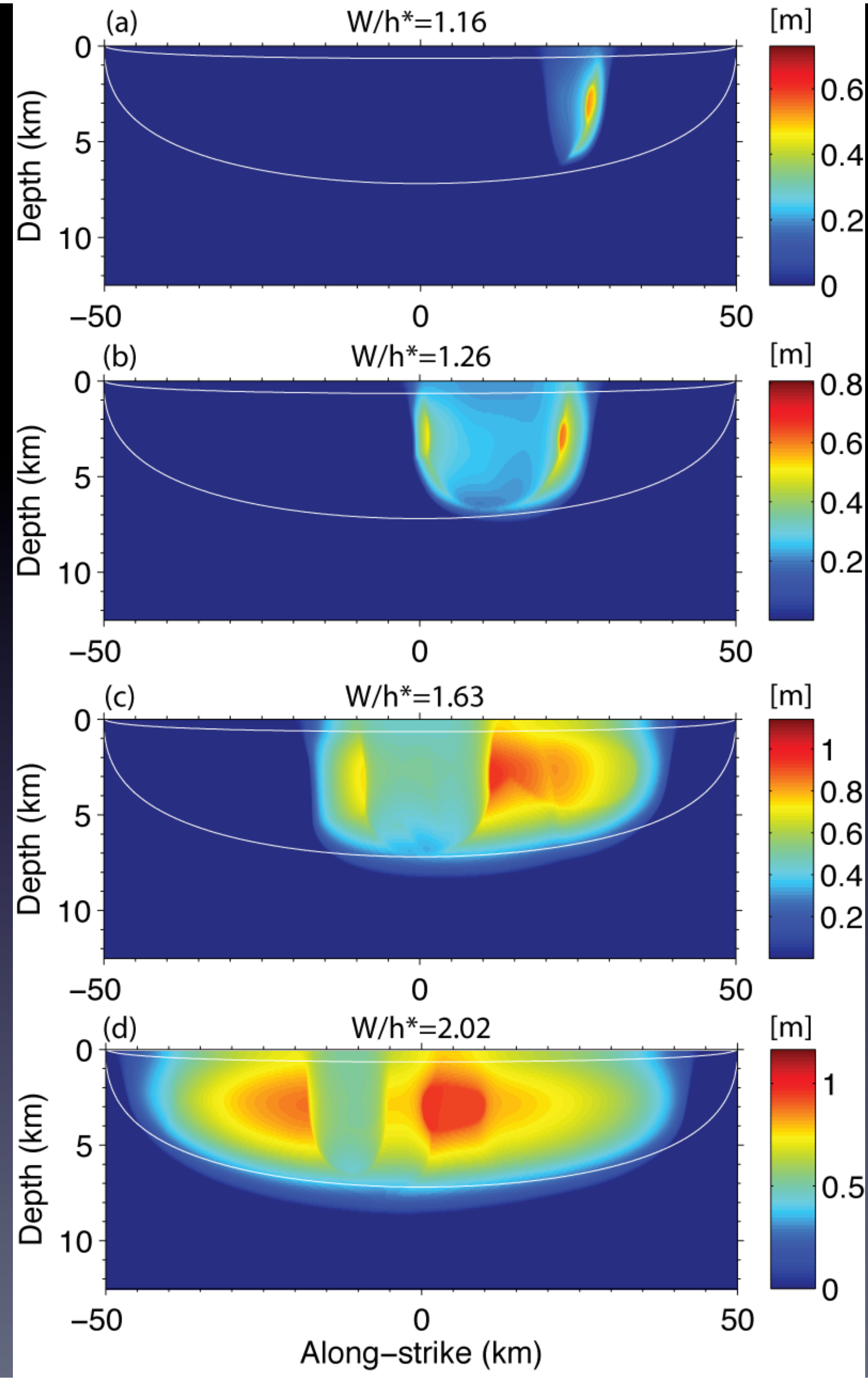


# Seismic coupling increases with *W/h**;

***coupling coef.* ~ 0.15 at *W/h** ~ 1.5**



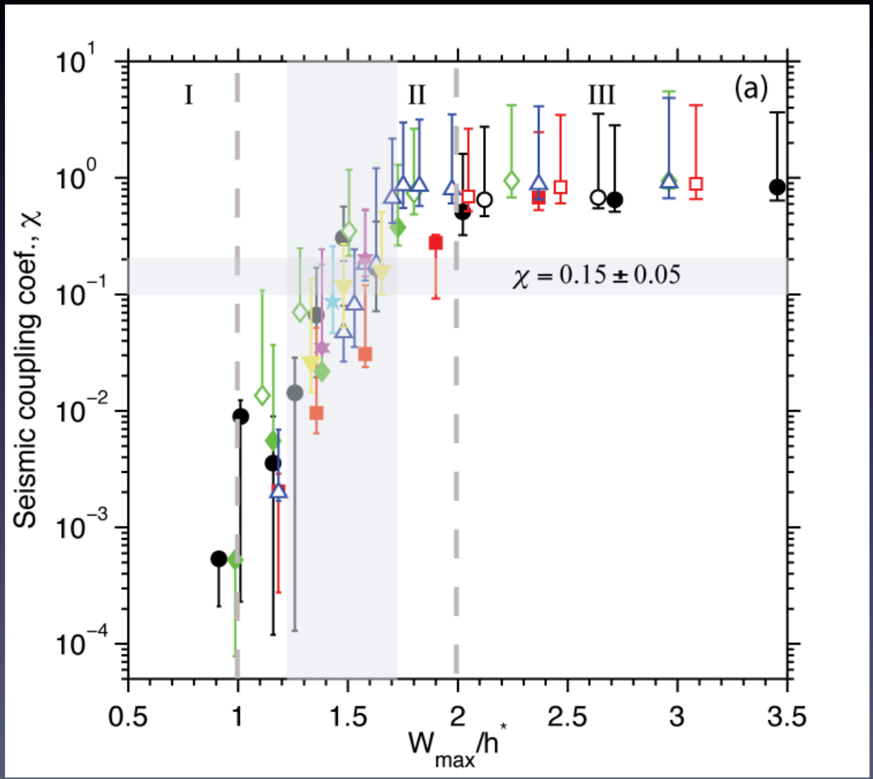

[Liu et al., 2012]

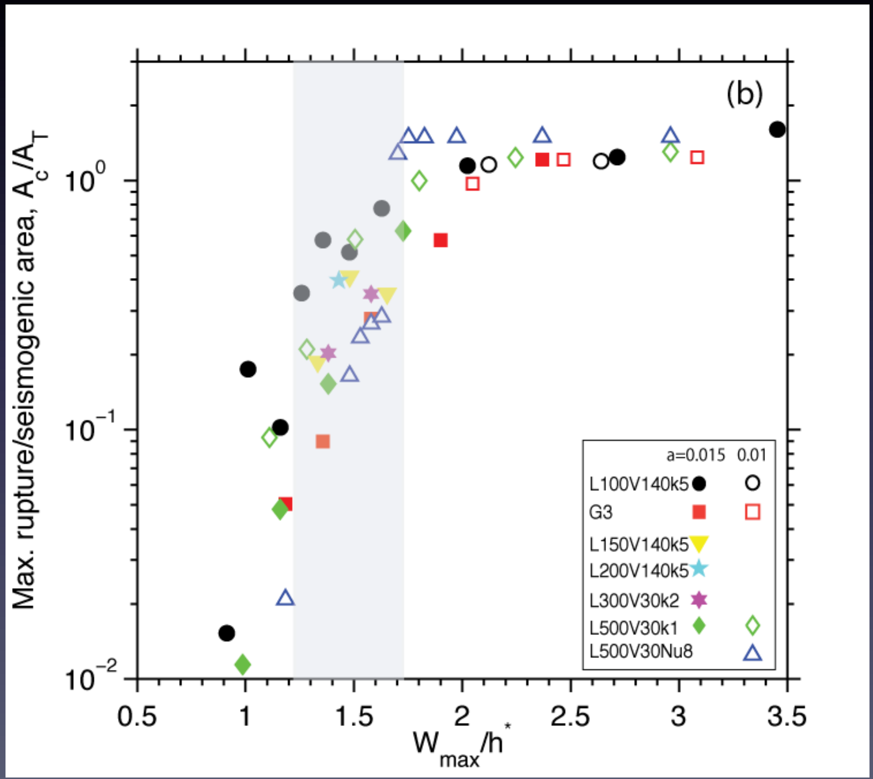


# Varying OTF fault parameters

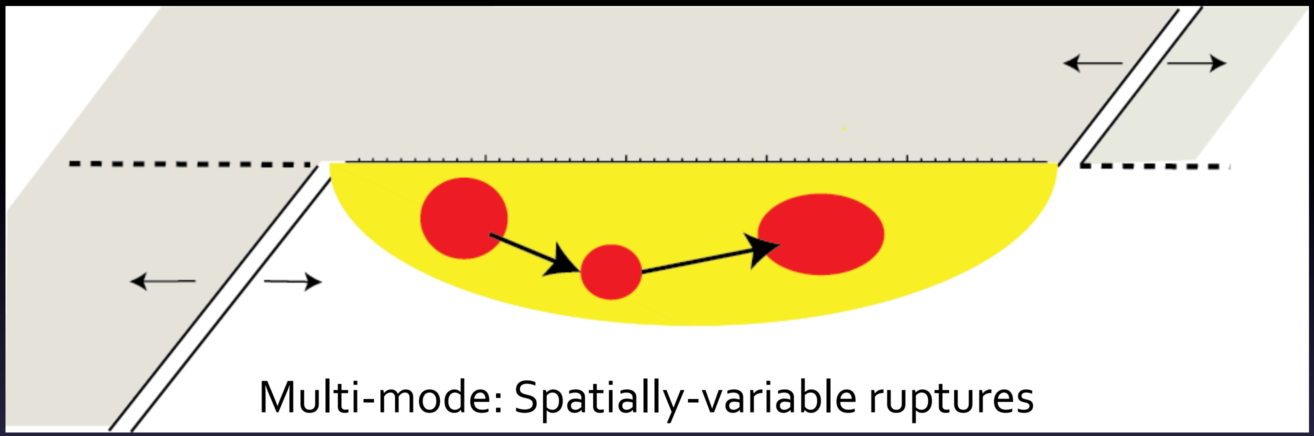
- OTF length: 100 – 1000 km
- Full spreading rate: 30 – 140 mm/yr
- Thermal model: (1) half-space cooling, (2) visco-plastic.

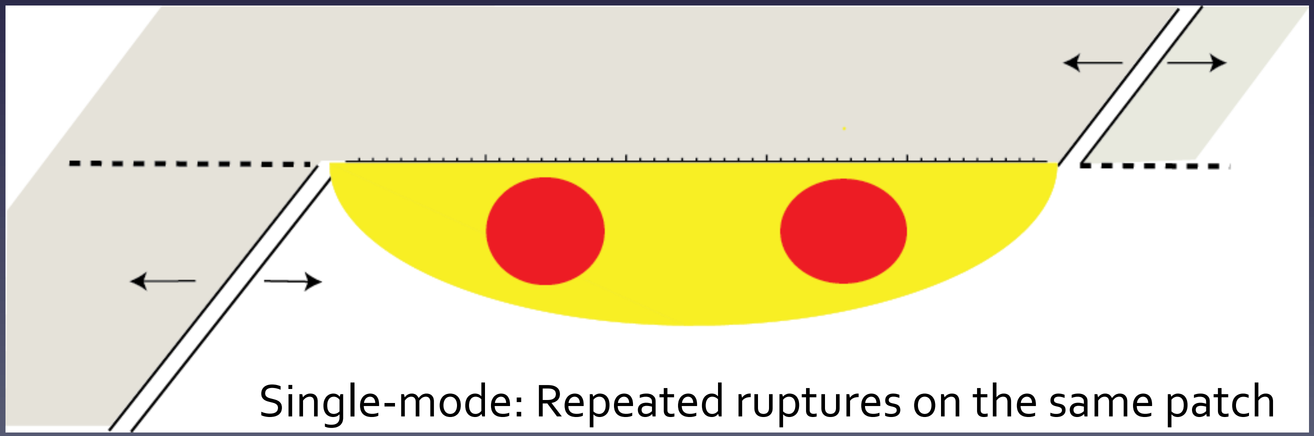
→ W/h* ~ 1 – 3



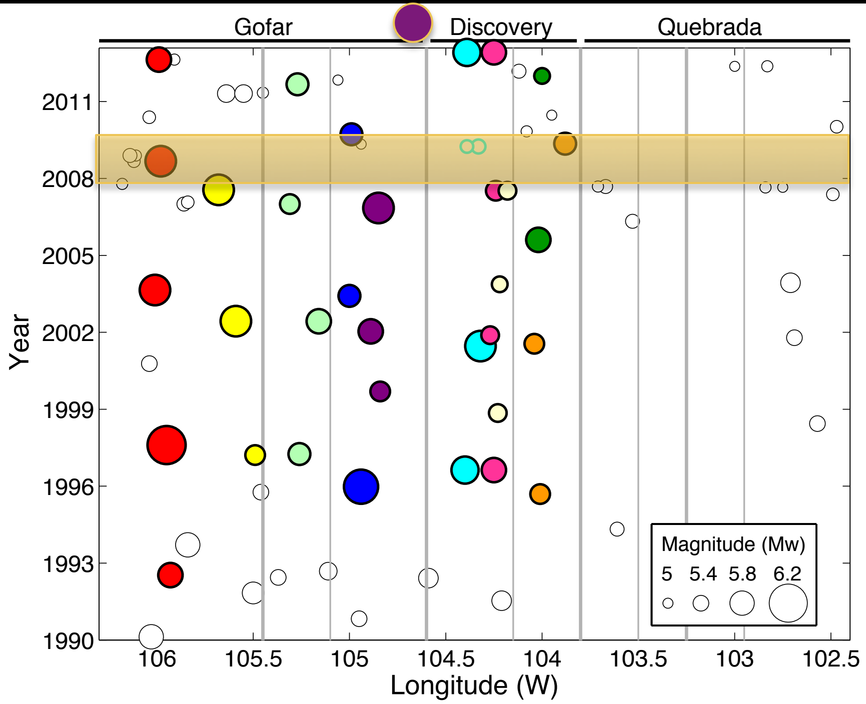
# “Multi-mode” vs “single-mode” seismogenic zone

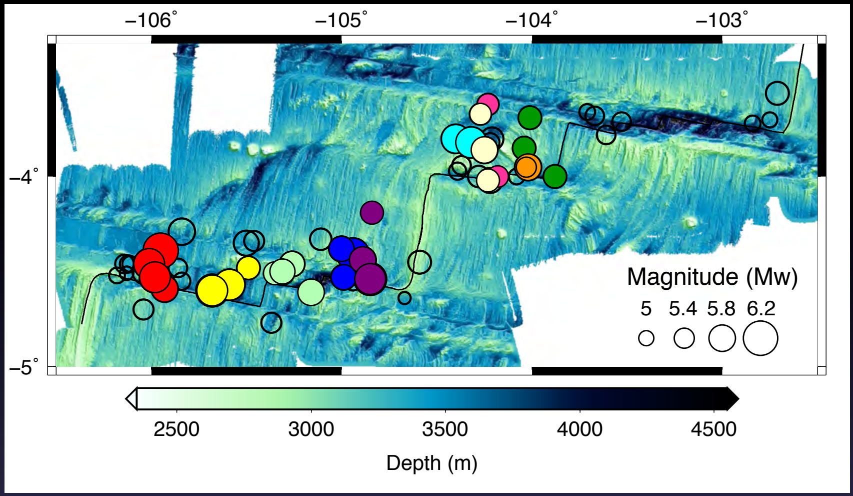



[conceptual model based on Boettcher and Jordan, 2004]

# Discovery and Gofar Transform Seismic Cycles




*[McGuire, 2008; updated 2014]*

# 2008 QDG  OBS Experiment

**Quebrada, Discovery, Gofar Fault System**

The first local observations of the end of an oceanic

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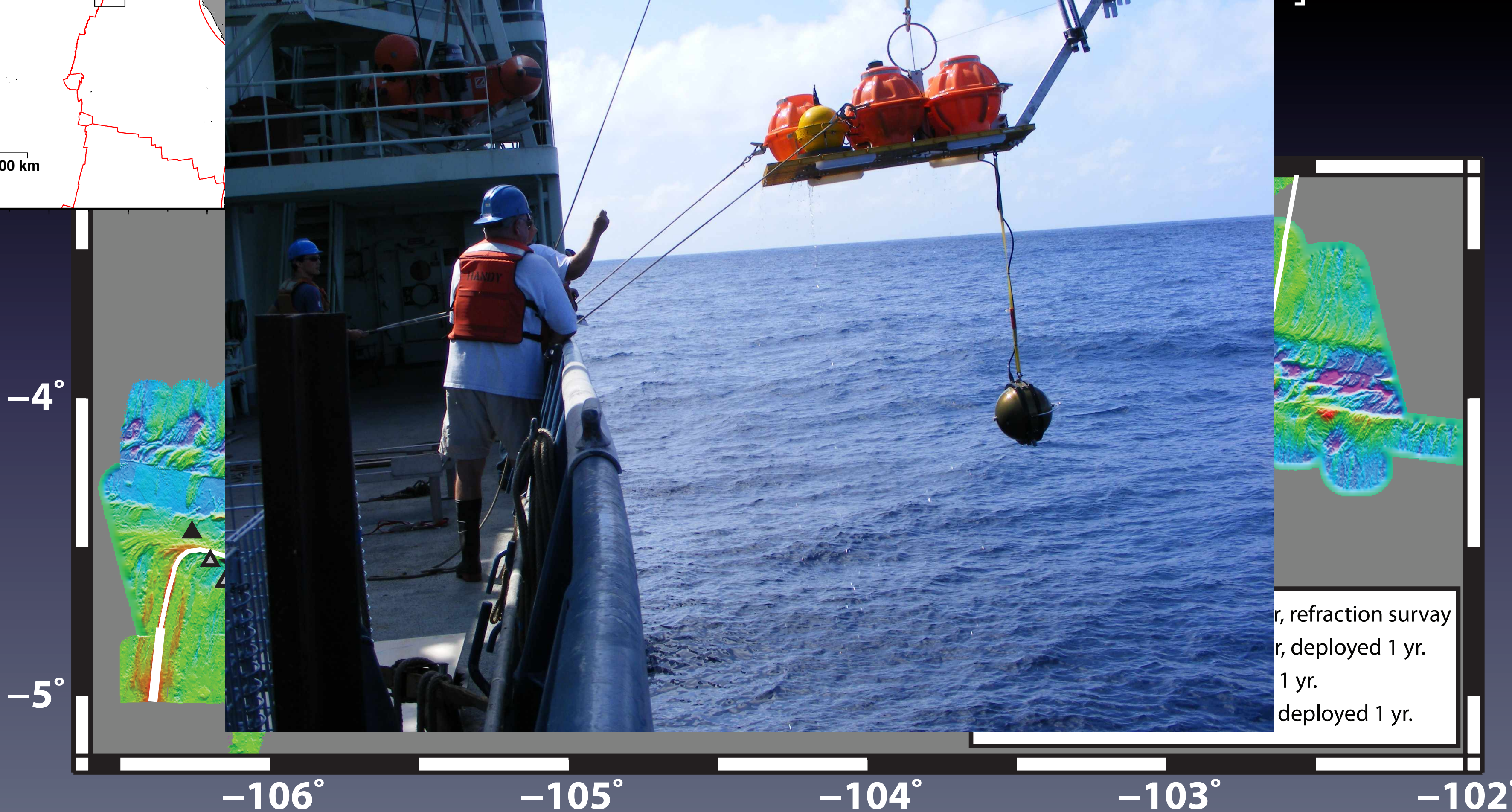
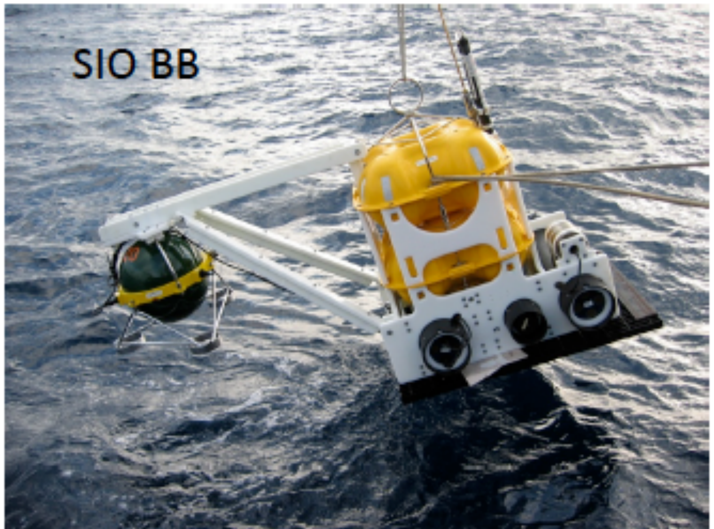
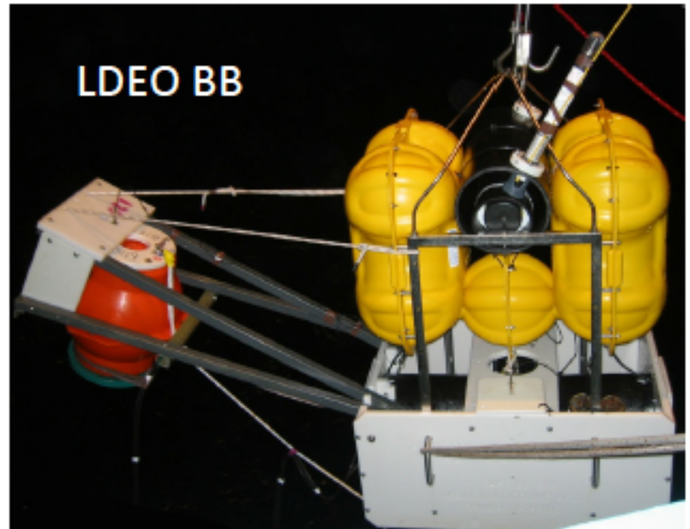
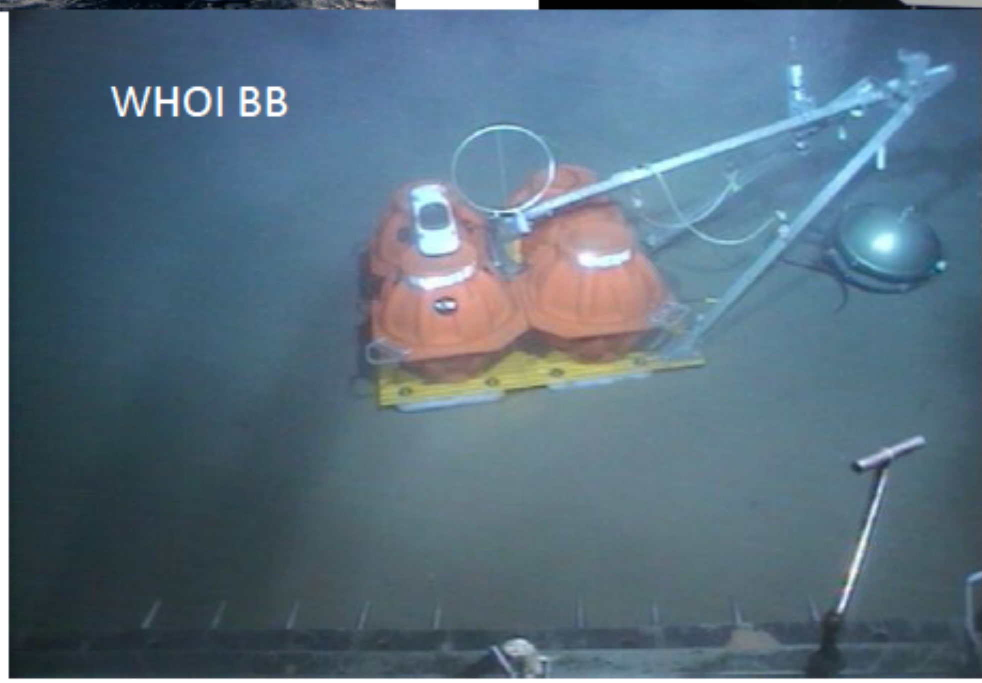




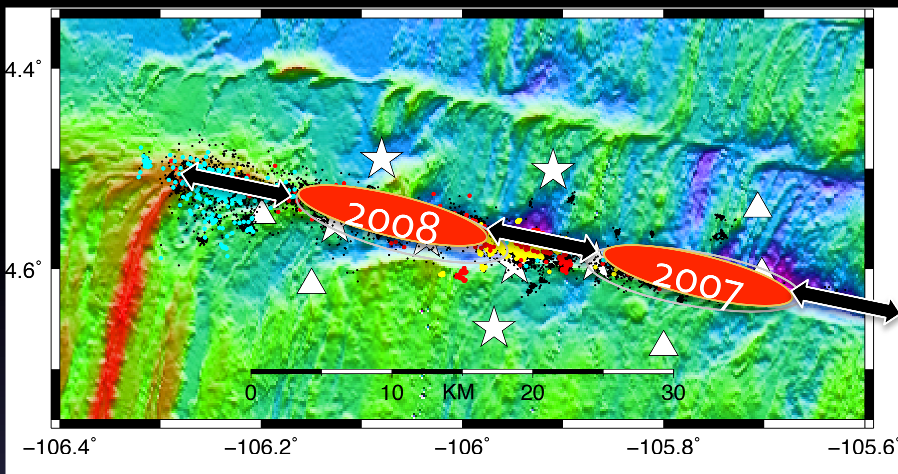

Combined:

Broadband: 103
Short-period: 96

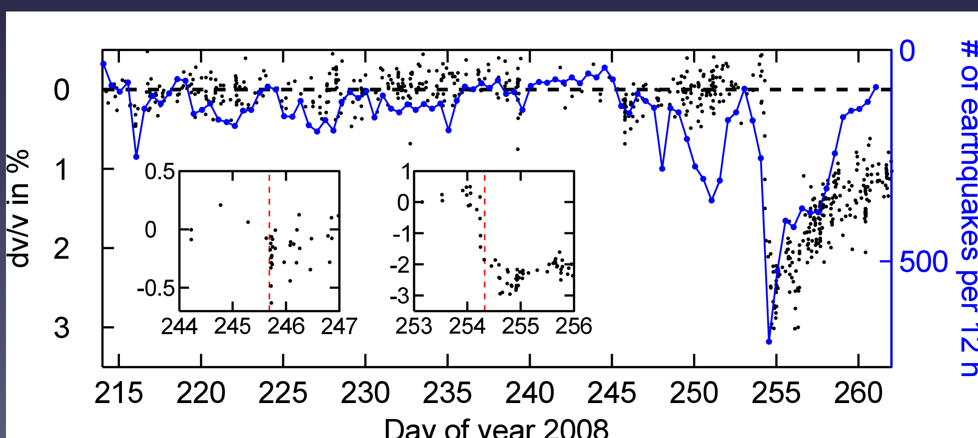


# Western Gofar Fault (G3)

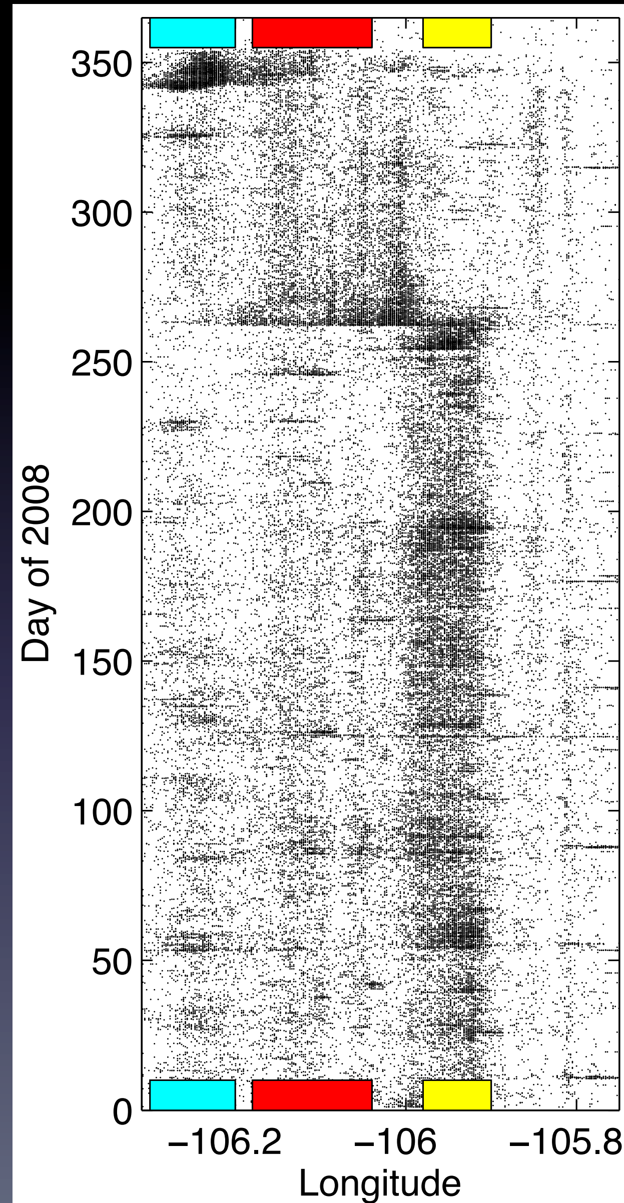
***Western Gofar Fault***



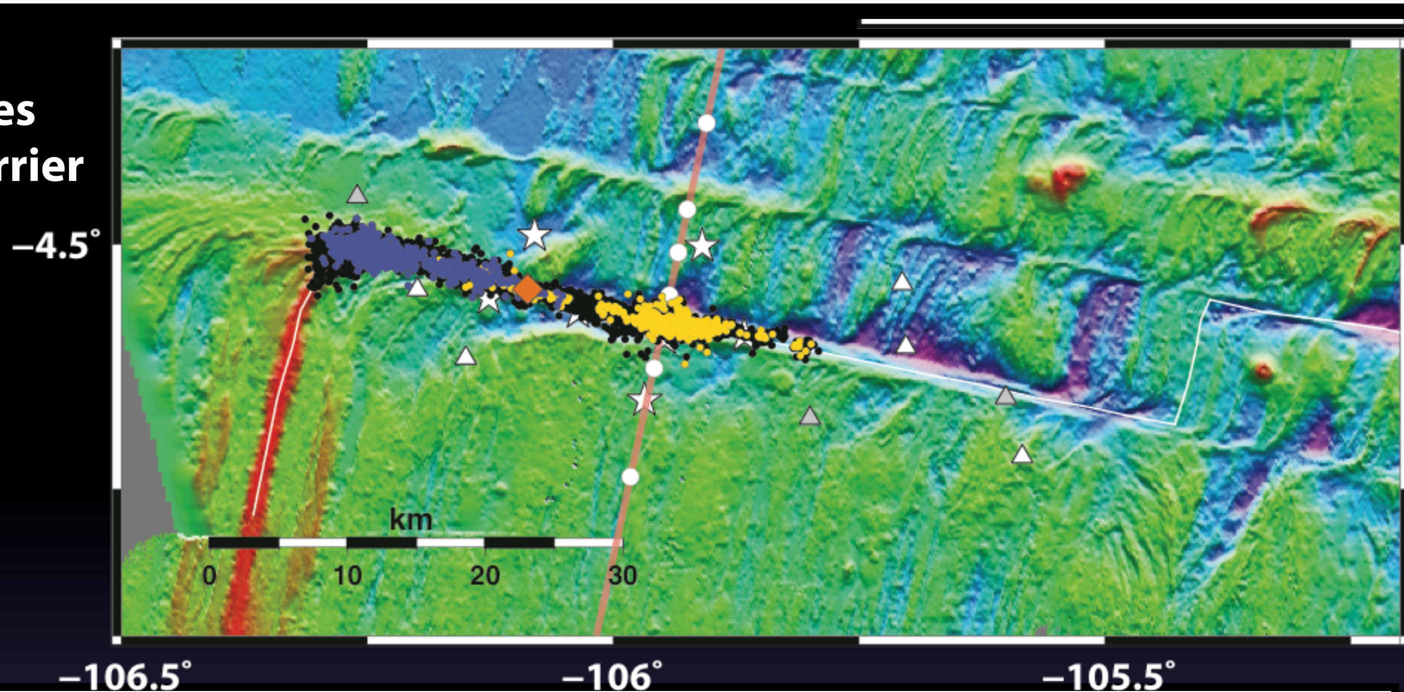

***Fault zone velocity change during 2008 foreshock***

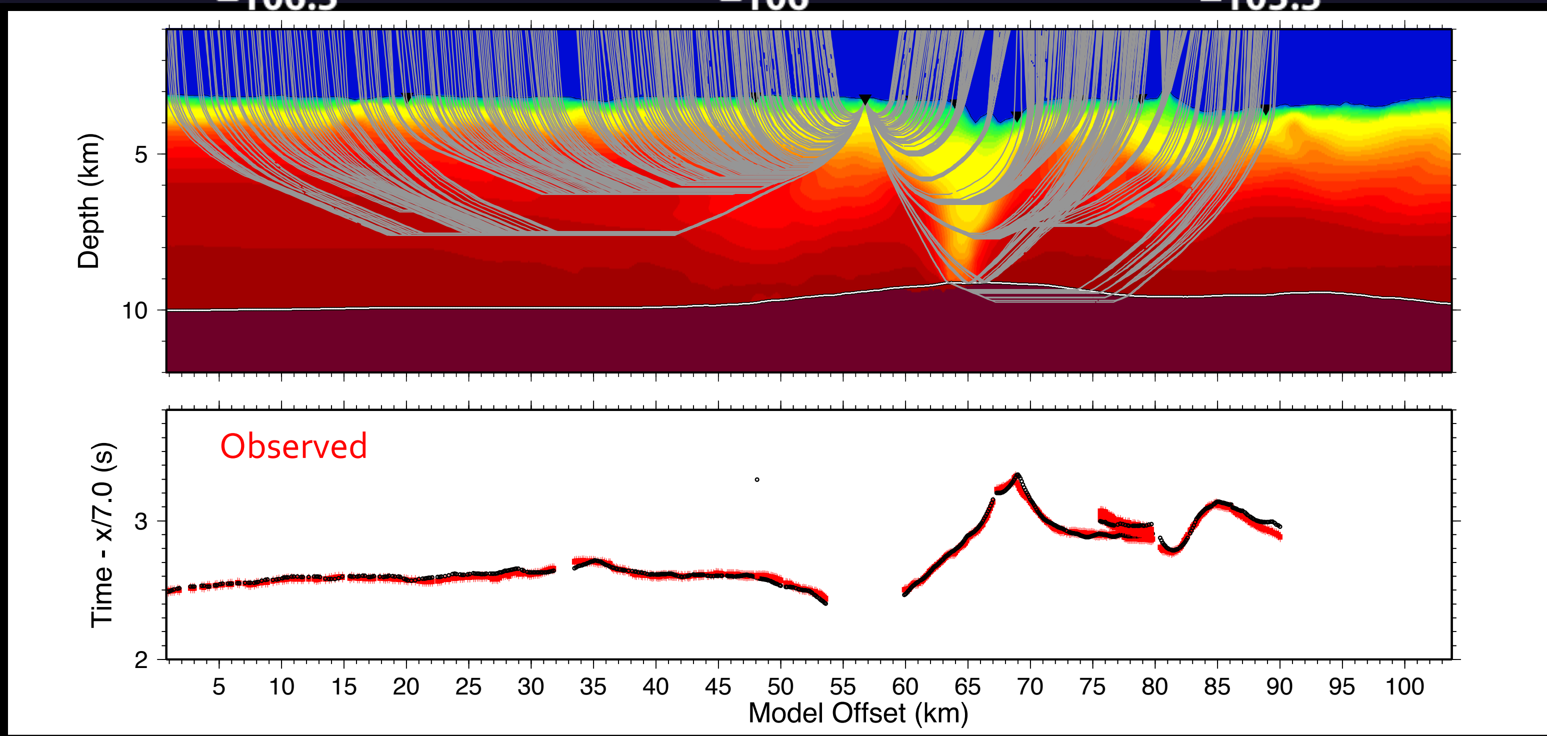



*[McGuire et al. 2012; Roland et al., 2012]*

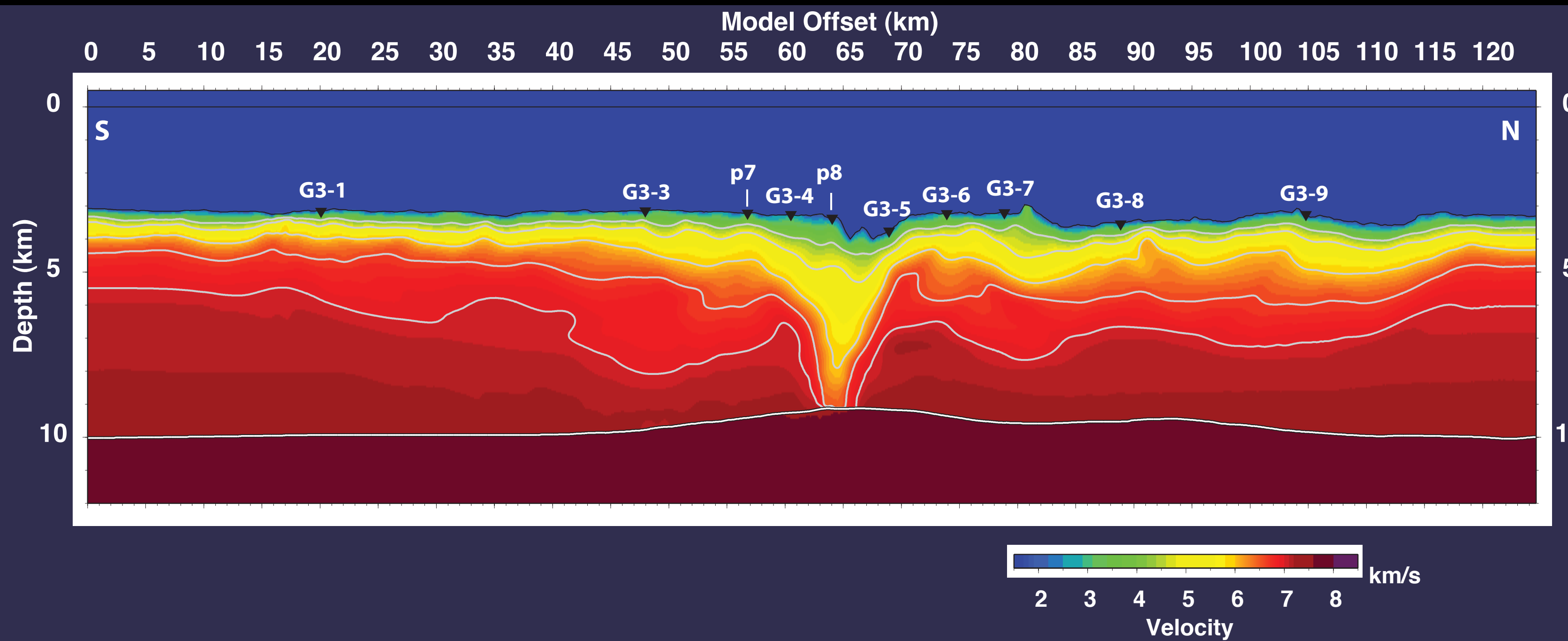


# Physical Properties of the rupture barrier



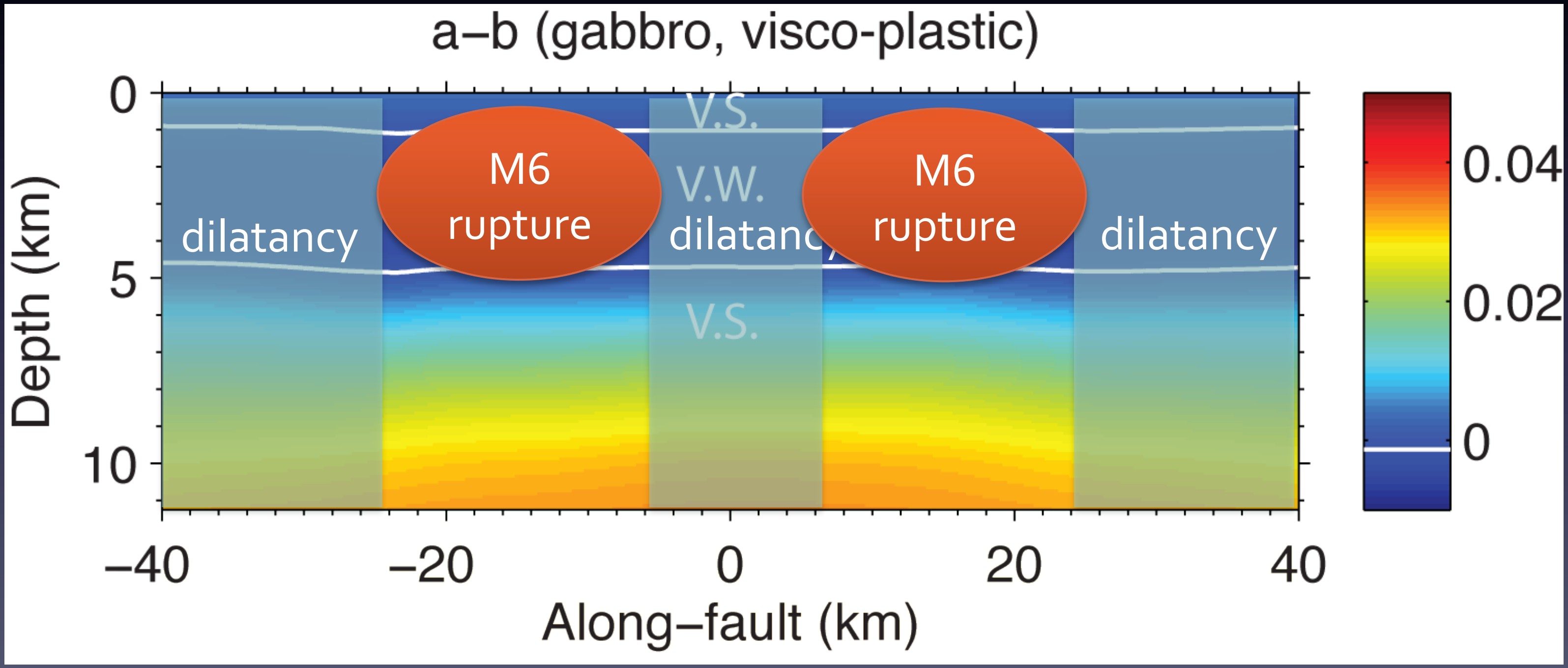
# Interpretations of imaged LVZ




- Intense fracturing associated with shear strain [Trehu and Purdy, 1983; Chester et al., 1993; Cochran et al., 2009; Yang et al., 2009…]
- Material alternation [Bonatti, 1978; Detrick and Purdy, 1980; White et al., 1984; Detrick et al., 1993; Faulkner et al., 2003…]

# The Gofar M6 rupture barrier

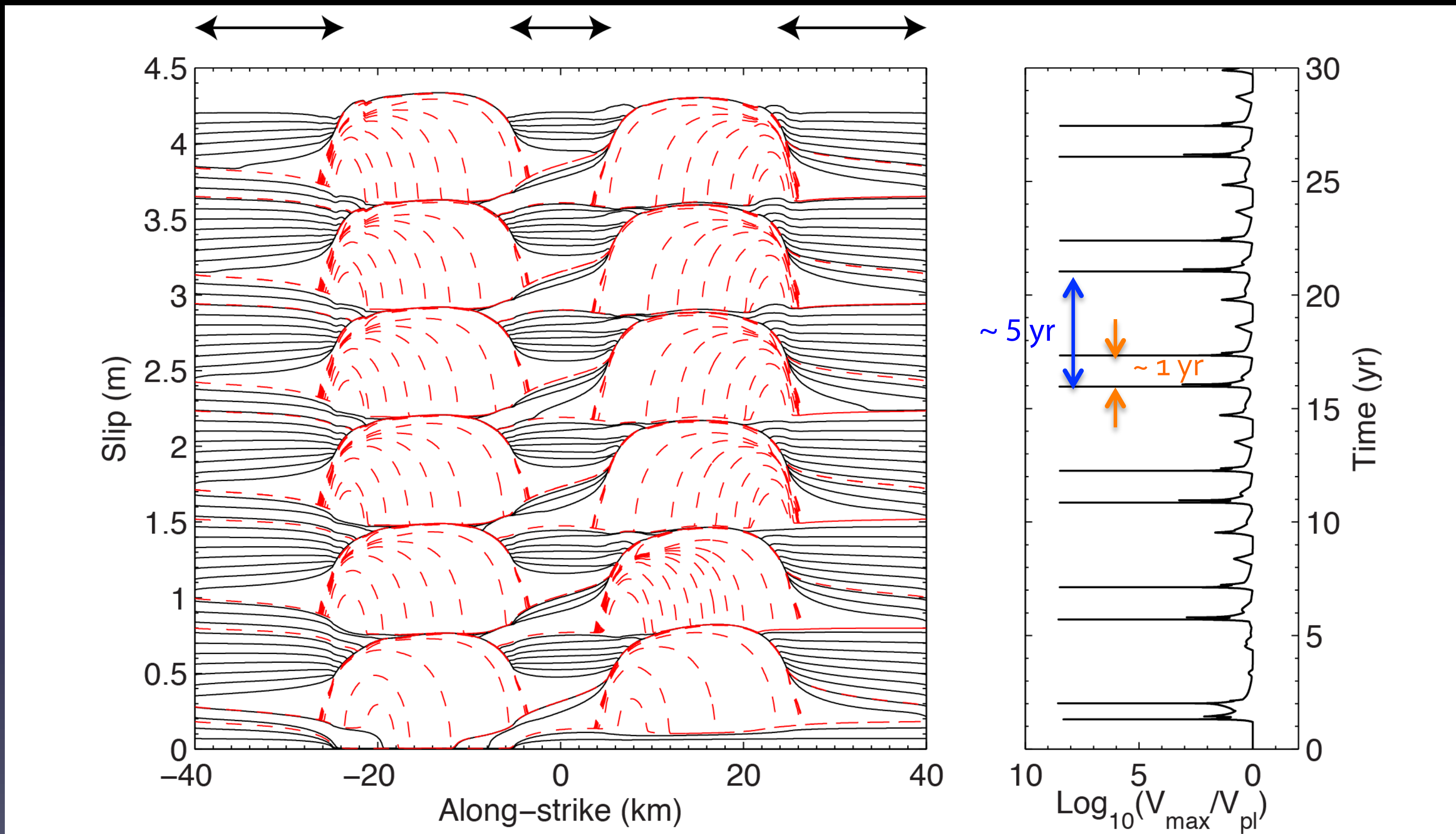
- **Low velocity zone → Fault-zone with enhanced fluid-filled porosity, 1.5-8%, to explain 10-20% drop in P velocity.**
- ***Dilatancy-strengthening*** as an effective rupture stabilizing mechanism [Segall and Rice 1995; Segall et al., 2010, 2012; Liu et al., 2010; *Liu, 2013*].




Thermal model [Behn et al., 2007; Roland et al., 2010]

Rupture segmentation due to alternating VS and VW frictional properties [e.g., Kaneko et al., 2010]

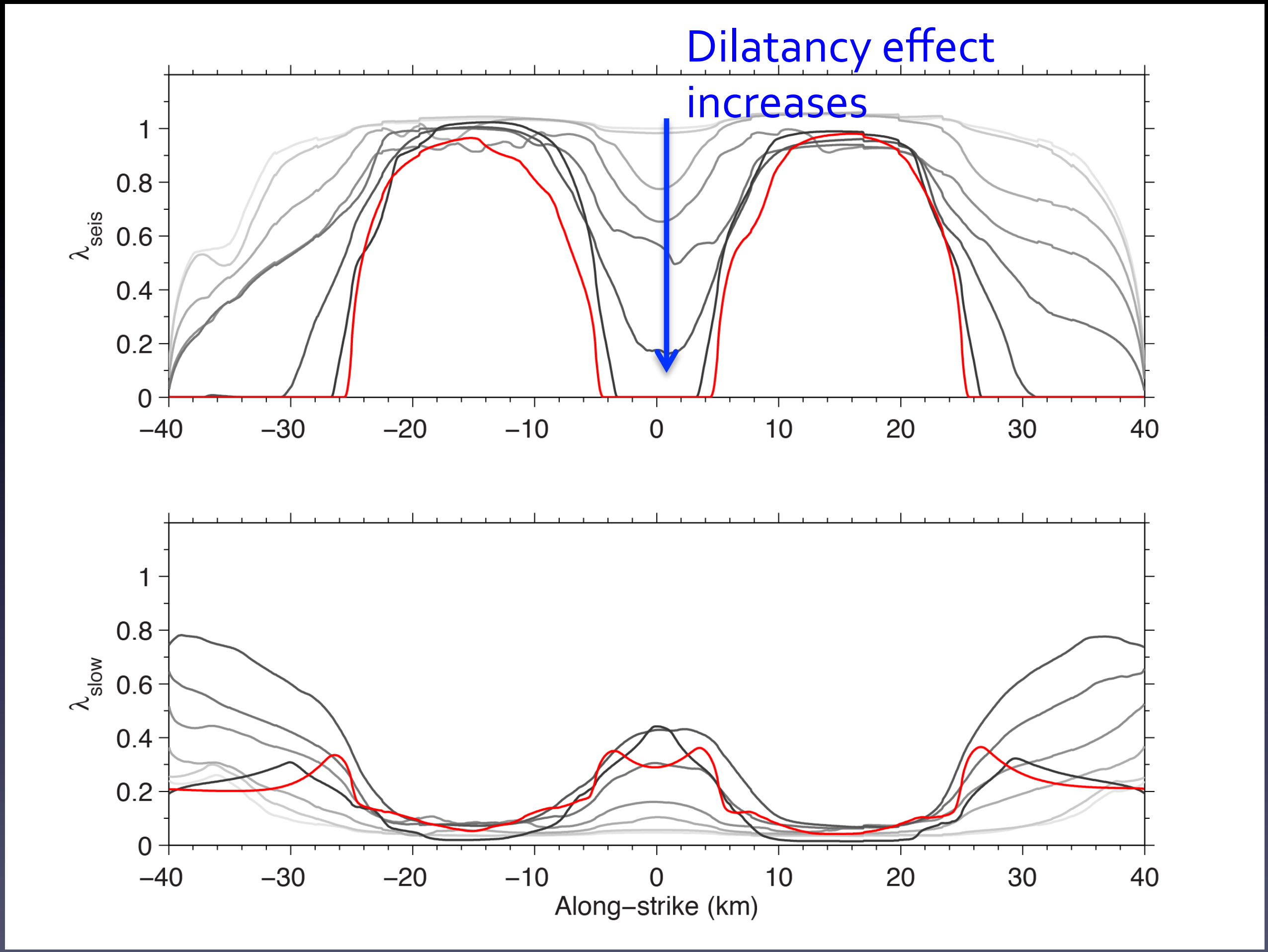
# As dilatancy effectiveness increases



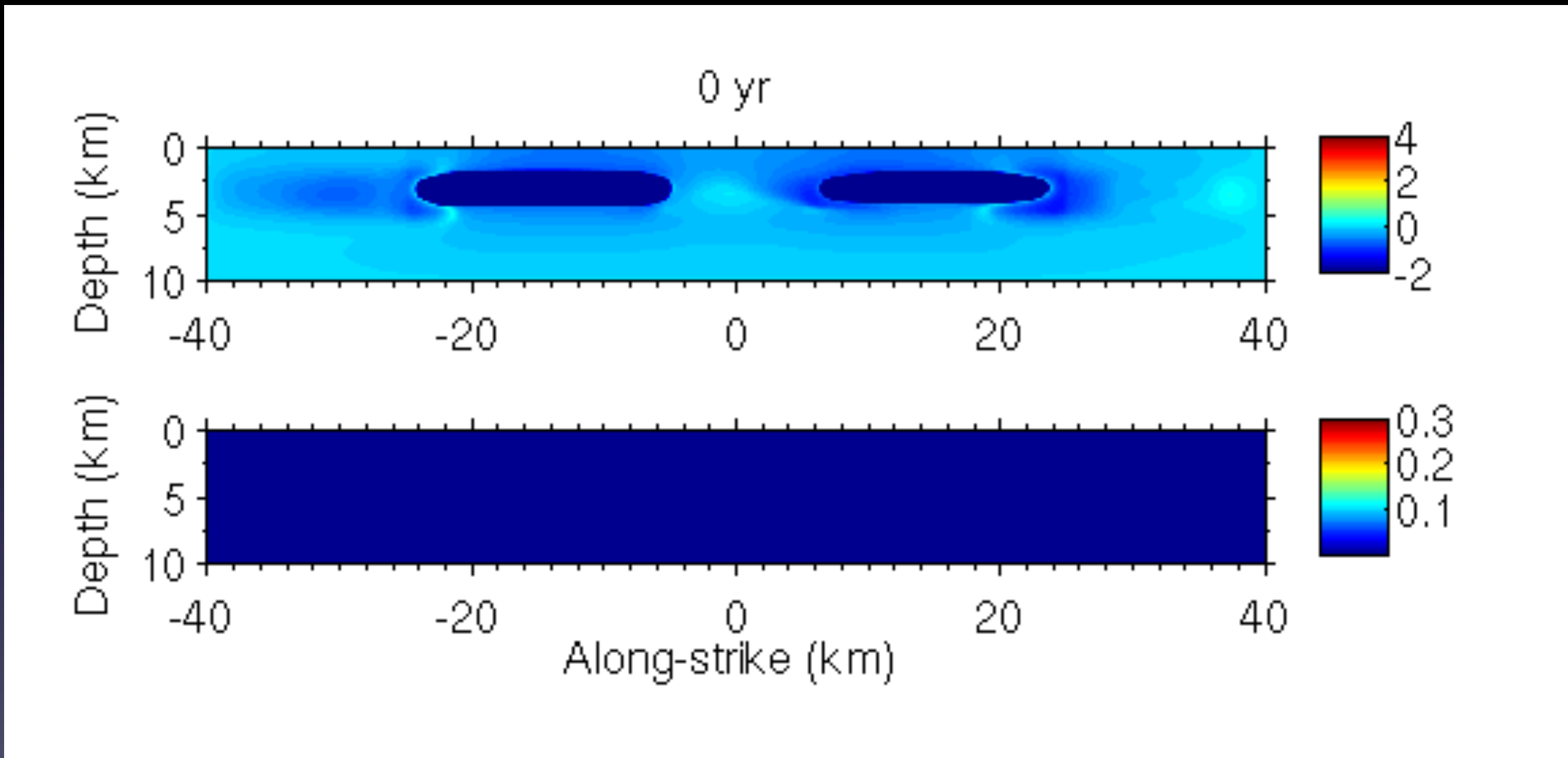

Porosity: 5%

Dilatancy coefficient: $2 \times 10^{-4}$ [Samuelson et al., 2009]

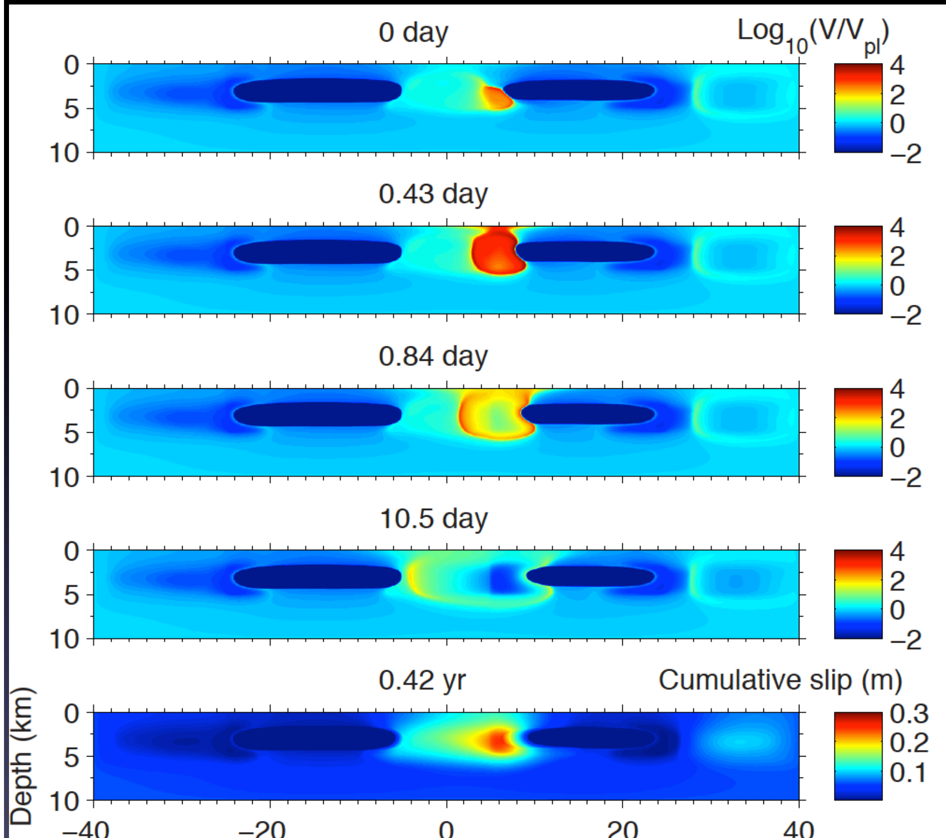
# Seismic coupling variation with dilatancy

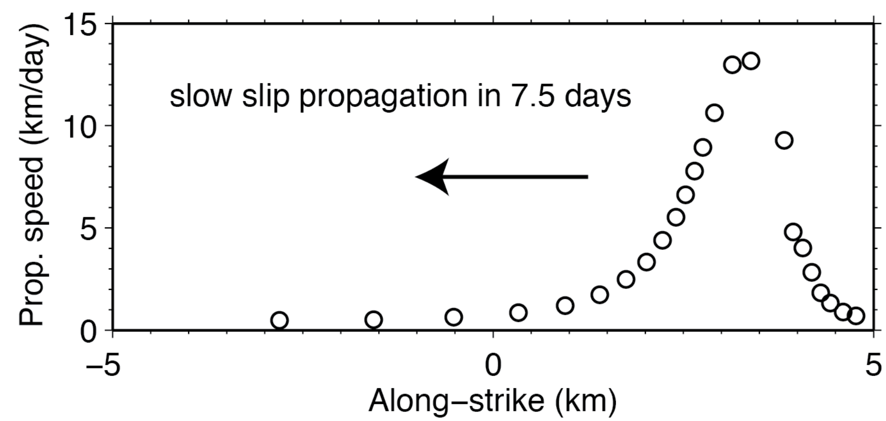


# Aseismic transient slip in the "barrier" zone



# Slow slip propagation in the dilatancy zone




Consistent with observations from **earthquake swarms** on continental and oceanic transform faults [e.g., Lohman and McGuire, 2007; Roland et al., 2009]:

- Stress drop: **10-100 kPa**
- Hypocentral migration speed: **0.1-1 km/hr**

**Aseismic creep transients are the primary process driving swarms on strike-slip faults → Seafloor geodesy**

# Conclusions

- Without introducing small-scale frictional heterogeneities, model results indicate an OTF segment can transition between seismic and aseismic slip over many earthquake cycles.
- Low seismic coupling coefficient of ~ 0.15 is reached when the seismogenic zone depth range is 1.2-1.7 times of earthquake nucleation size.

- Strong dilatancy-strengthening effect, due to enhanced fault-zone porosity, can stop earthquake propagation on an OTF, resulting in rupture segmentation patterns as observed on Gofar Fault, East Pacific Rise.
- Modest aseismic creep in the rupture "barrier" zone may be the driving mechanism for earthquake swarms on transform faults, fundamentally different from mainshock-aftershock Coulomb stress triggering.