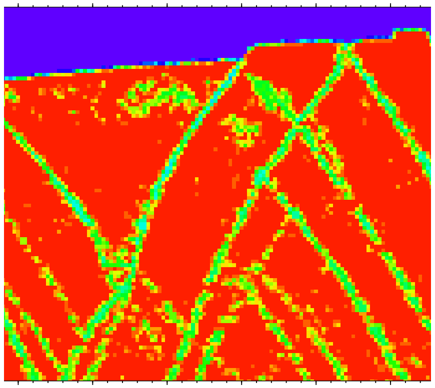
Deformation & Strength of the Incoming Plate:
Observations & Simulations



Magali Billen

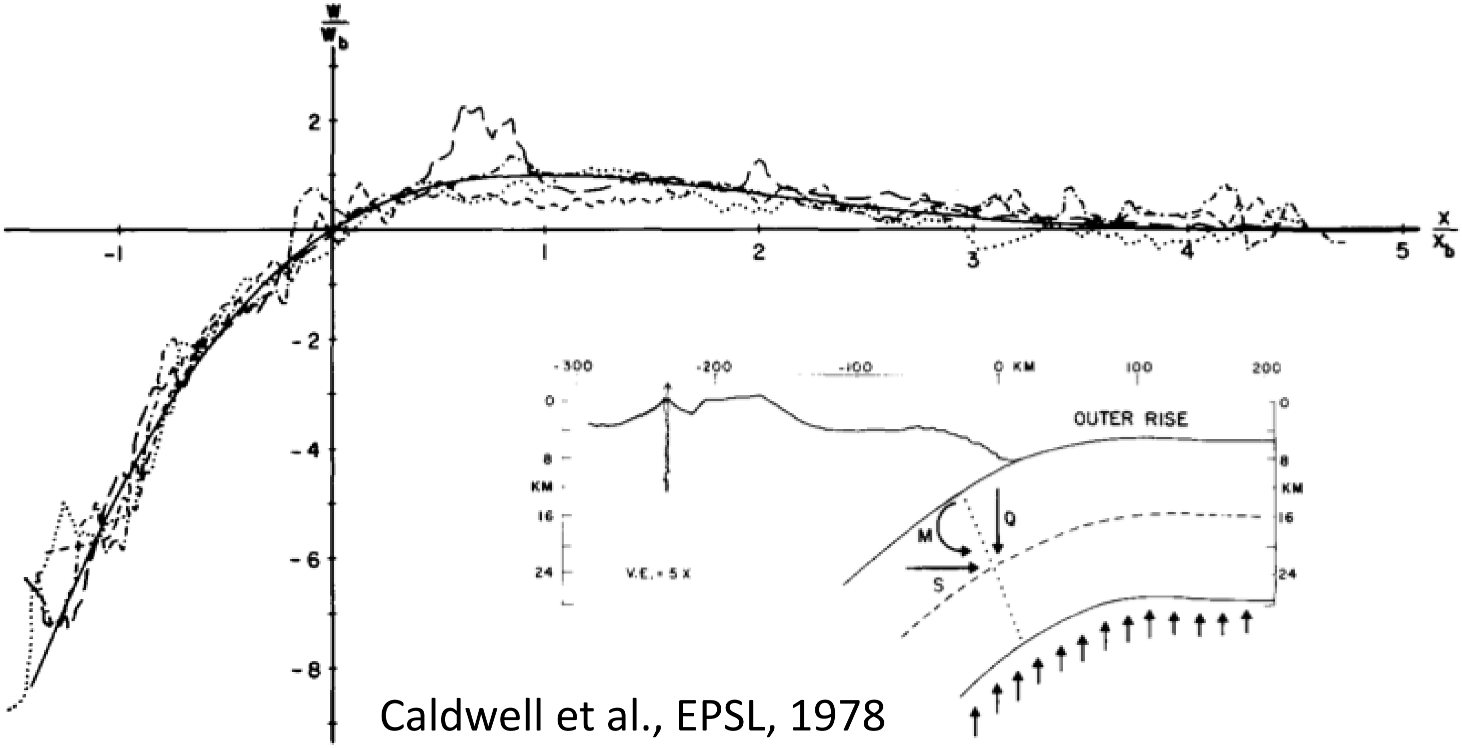
with contributions from

M. Gurnis, E. Cowgill,

E. Buer, J. Saunders,

T. Gerya, M. Faccenda, J. Naliboff

Early Models of Plate Bending



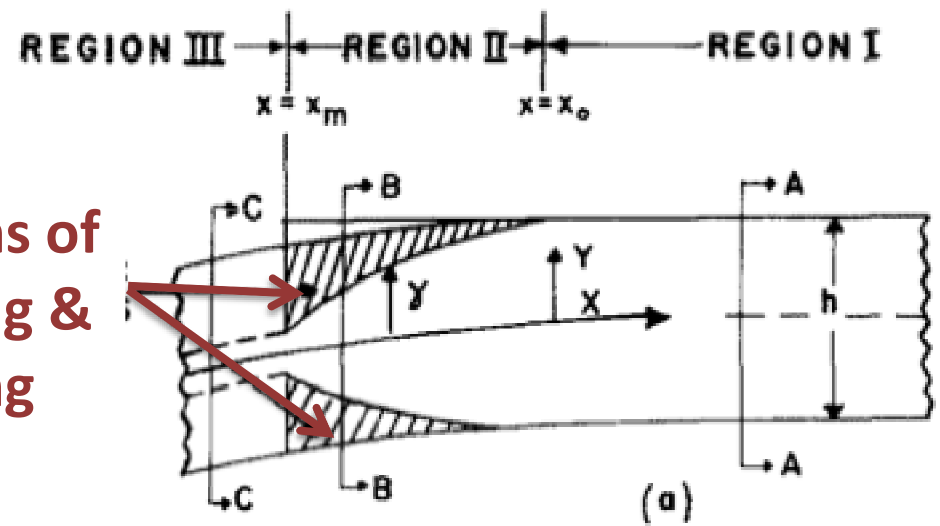
Caldwell et al., EPSL, 1978

- Bathymetry matches that of a **bending plate**.
- Profile can be fit by plates with different **rheology** and/or different **boundary forces**.

Subducting Plate Rheology

- Elasto-visco-plastic strength depends on plate age
- Strength also changes as the plate bends
- Plate suffers permanent deformation
  - yielding & faulting

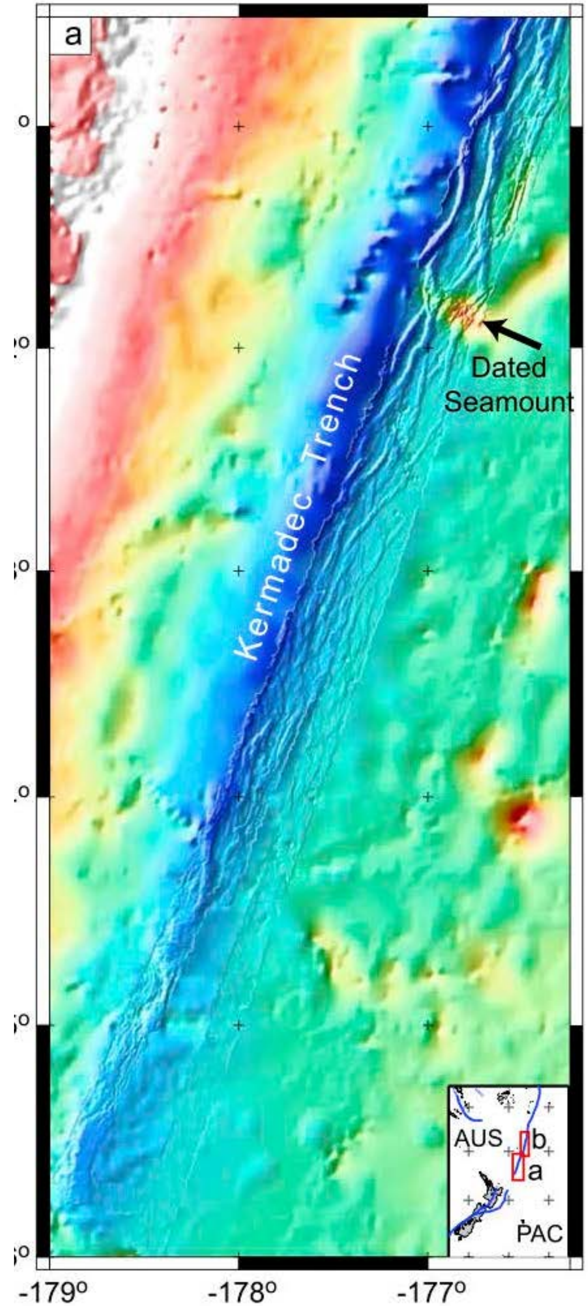
Regions of Yielding & Faulting



Turcotte et al., TECTP, 1978
(Goetze & Evans, GJRAS 1979)

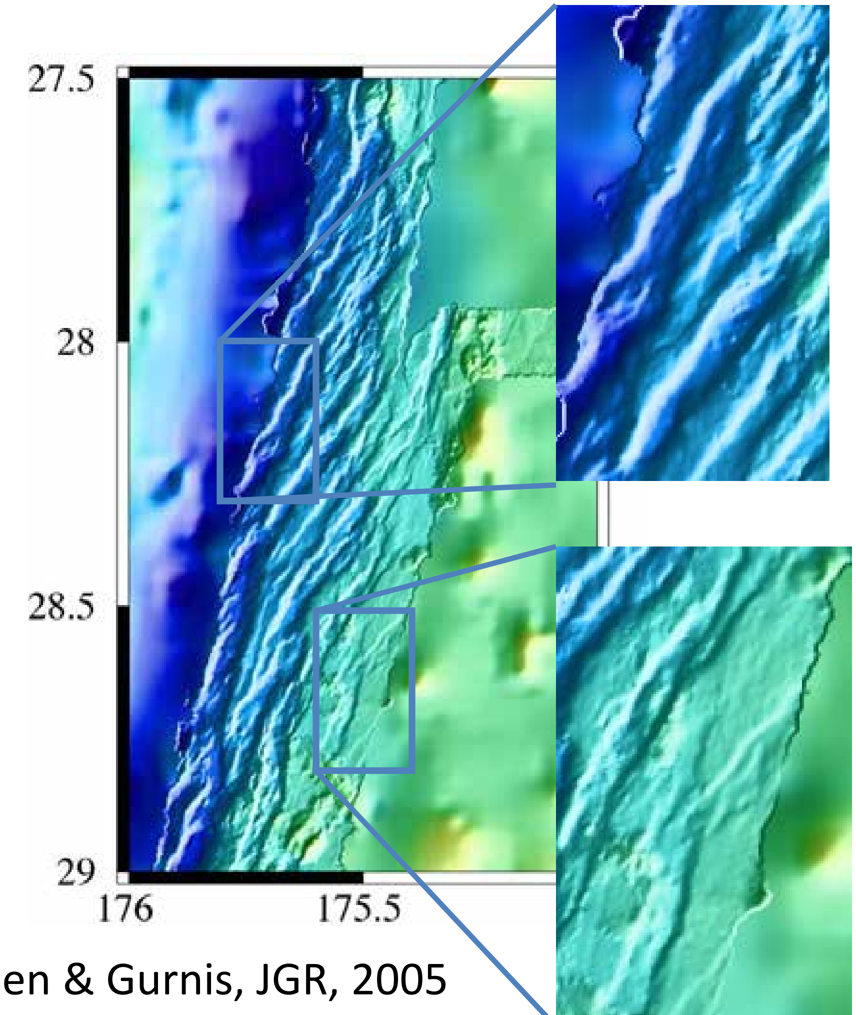
Outer-rise Faults

- Found at all trenches
- Can dip towards & away from trench (30-60 degrees)
- New & reactivated faults
- Faults grow in length & throw toward the trench.
- Spacing & length varies.



Masson, Marine Geophys. Res., 1991;
Massel, PhD., 2002

Outer-rise Faulting: Tonga



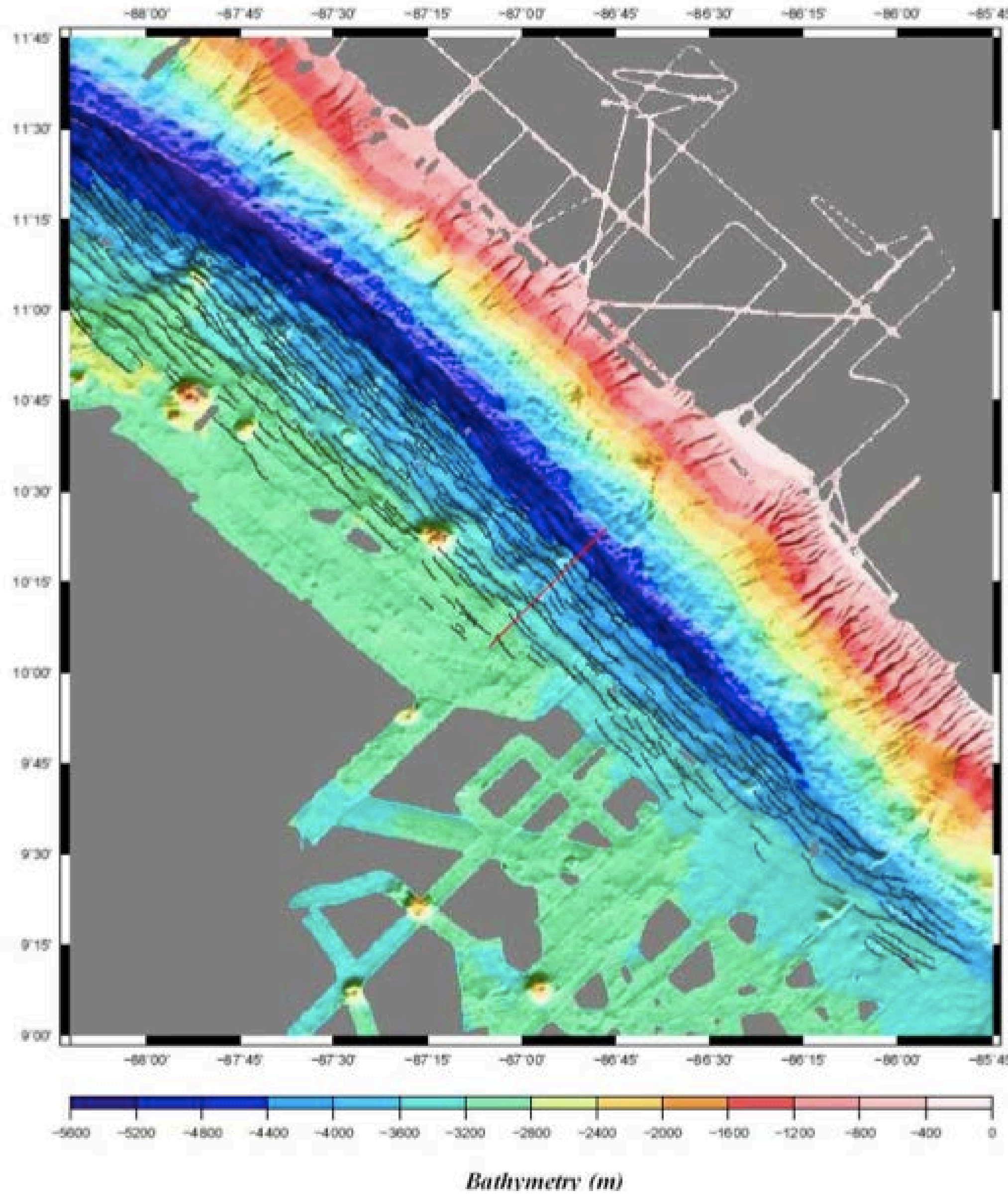
Billen & Gurnis, JGR, 2005

- Faults form sub-parallel to trench
- Abyssal-hill fabric is sub-perpendicular (Billen & Stock, 2001)
- Fault scarps are larger near the trench

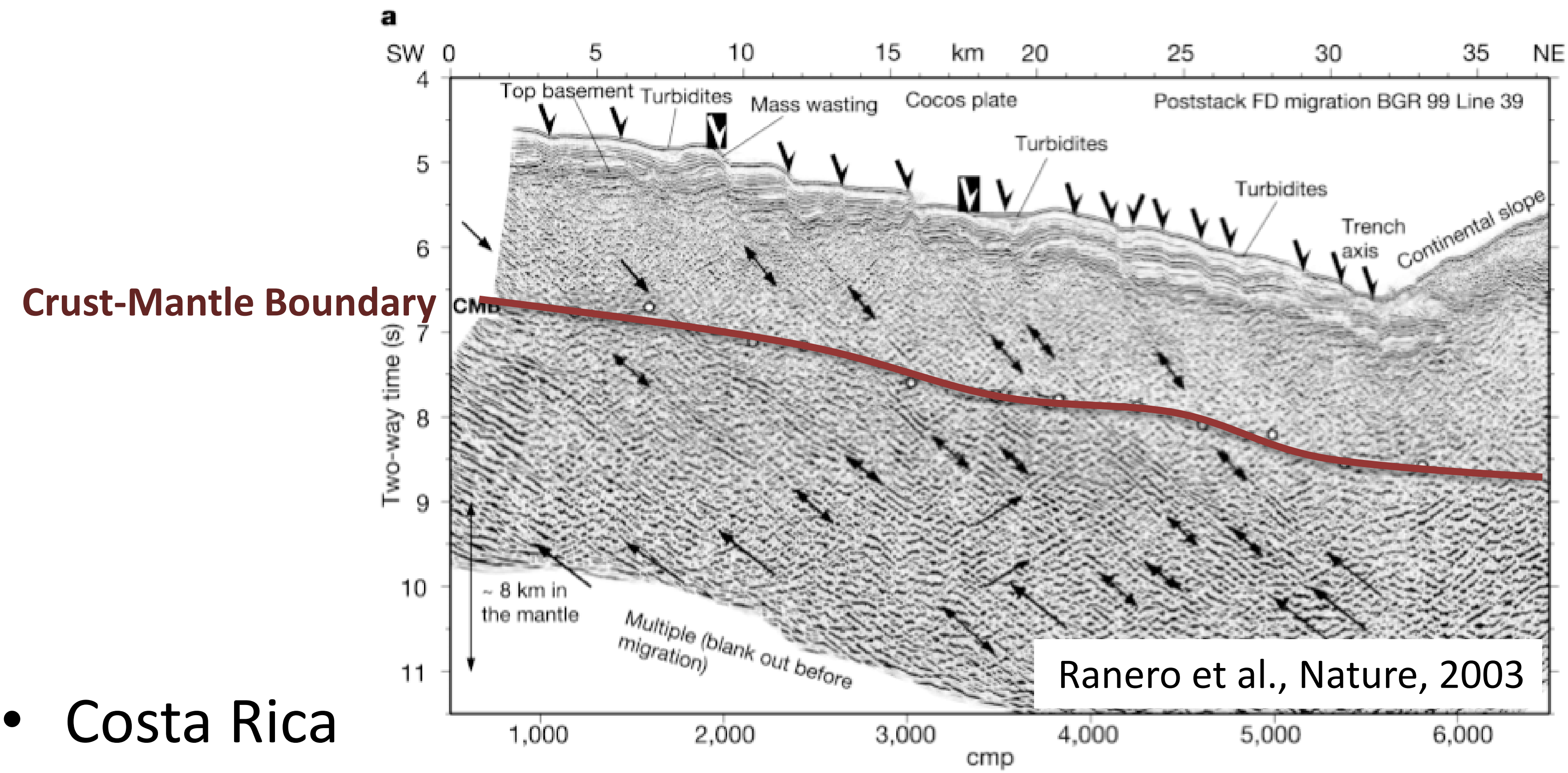
Outer-rise Faulting: Middle America

- Seafloor fabric is parallel to trench
- Outer-rise faults reactivate seafloor fabric

- *How deep do these faults go?*

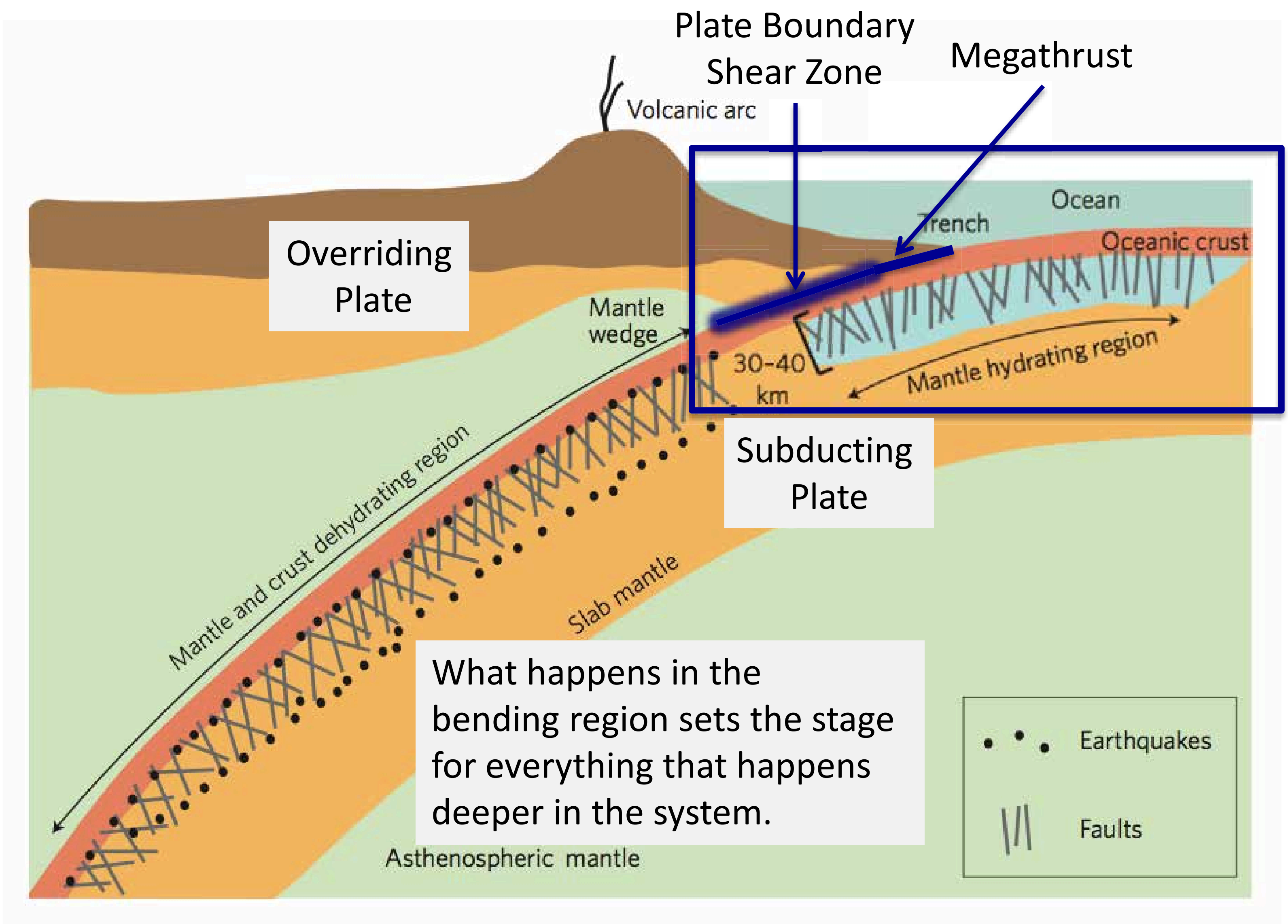


Outer-rise Faulting: Depth of Faults



- Costa Rica
  - Bright reflectors line-up with faults observed at the seafloor
  - Some reflectors clearly go deeper than the crust-mantle boundary (CMB).

Overview of the Incoming Subducting Plate



Using Outer-rise Faulting to Learn About Incoming Plate Deformation

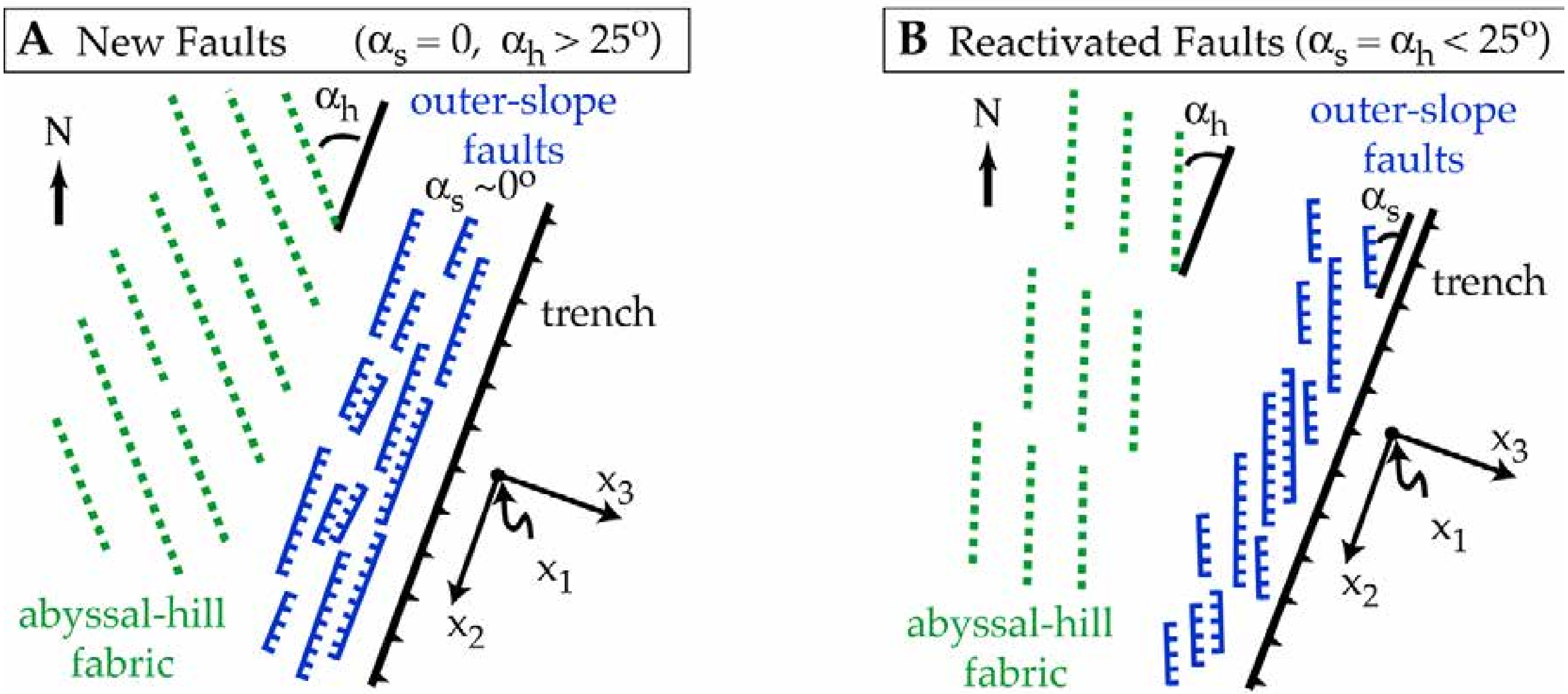
Observations & Analytic Models

1. What controls formation of new versus reactivated faults?
2. Do the characteristics of faulting provide insight into their formation?
3. Does faulting actually reflect deeper weakening of the plate or is it surficial?

Numerical Simulations

1. Does faulting reflect/depend on properties of the subducting plate or plate boundary shear zone?

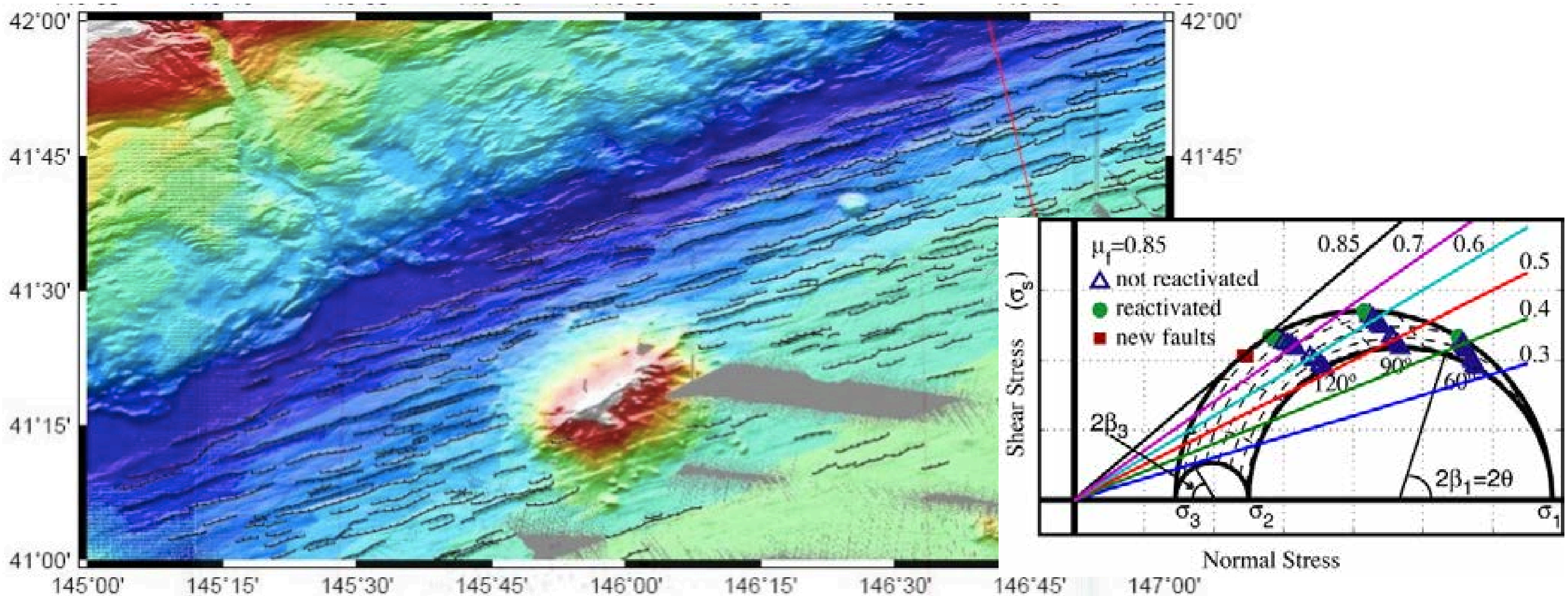
1. Frictional Strength of Outer-rise Faults



Billen et al., Geology, 2007

- Observation → Transition angle:
  - New faults form when seafloor fabric is ***mis-aligned*** by more than <u>25 degrees</u> from trench-parallel.

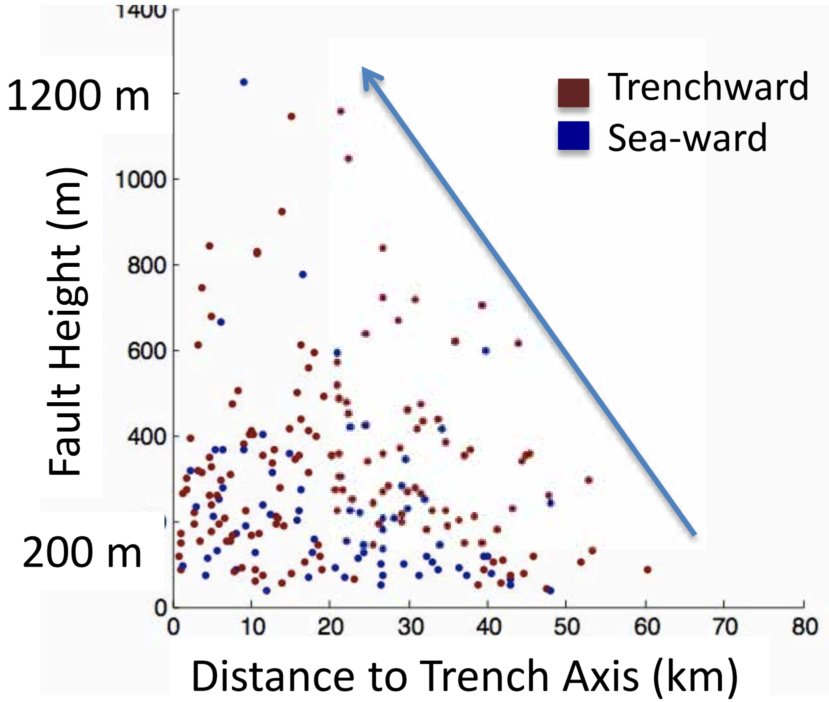
Transition angle constrains fault strength

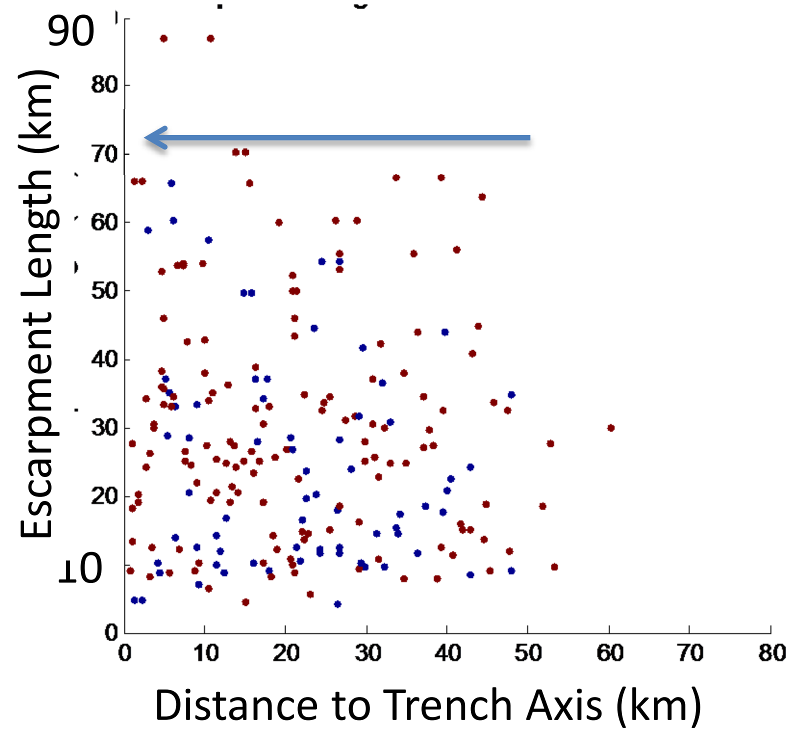


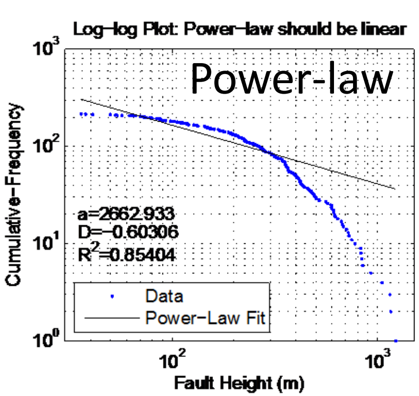
Billen et al., Geology, 2007

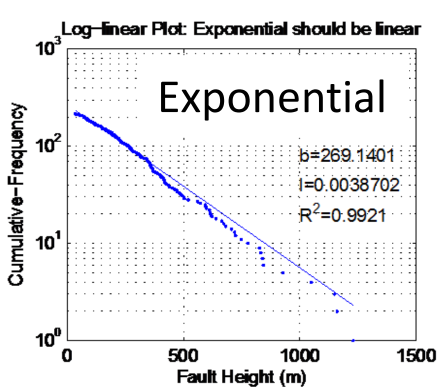
- 3D analysis of stress-state & transition angle = 25°
- Reactivated faults are **only 30% weaker** (0.6) than the crust in general (0.85)
- No pre-existing weakening, nor is it required

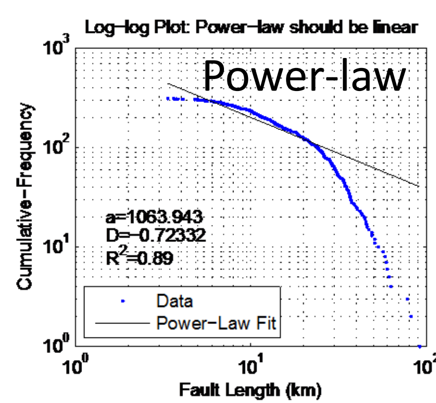
Faulting Characteristics: fit by **Exponental law**

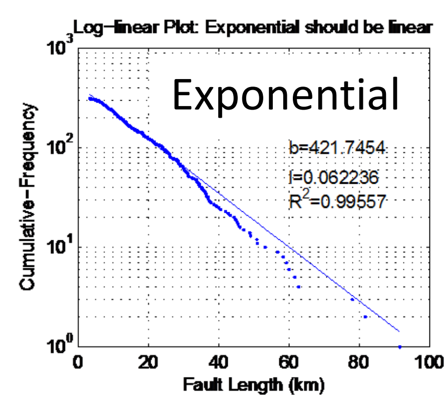












- Applied same analysis to Middle America and the Kuriles

What does exponental fit tell us?

- Analog models for ***extension***
  - transition from power-law to exponential-law as faults grow to fill layer thickness.
  - Power-law is indicative of simultaneous formation of faults and elastic interaction. *(Ackerman et al., J. Str. Geo., 2001)*

- Analog models for ***flexing*** of a plate:
  - exponential-law dependence for fault spacing: faults are anti-clustered.
  - neither law is a good fit for length or height.
  - Sequential formation of faults at moving bending axis.

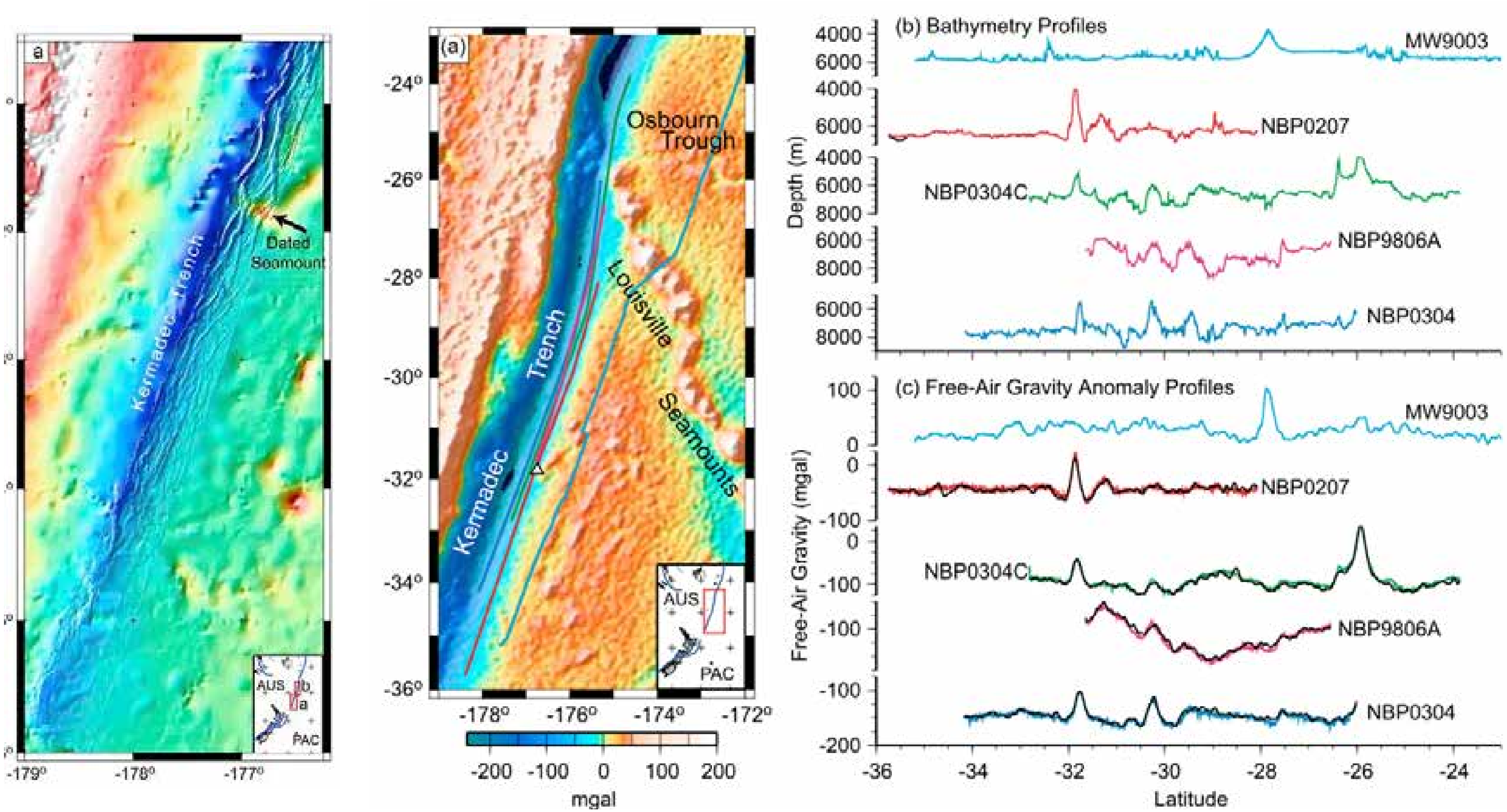
What does exponential fit tell us?

Correlations?	Spacing	Length	Height
Plate Age	+	no	no
Sub. Velocity	no	+	+
Shallow Dip	- (?)	+	+
New vs. React	- (?)	+	+
Cont vs. Ocean	- (?)	+	+

Saunders, Billen, Naliboff, unpublished

- Positive correlation between plate age & fault spacing
  - but fault spacing has a small variation (2.0 – 2.9 km).
- Length & height: positive correlation with all *but* age.
- Three locations is not sufficient to determine 1st order factor
- Tonga: large difference in sub. velocity & slab dip
  - BOTH should lead to higher strain-rates in the bending region.

3. Weakening of the Subducting Plate



Billen and Gurnis, JGR, 2005

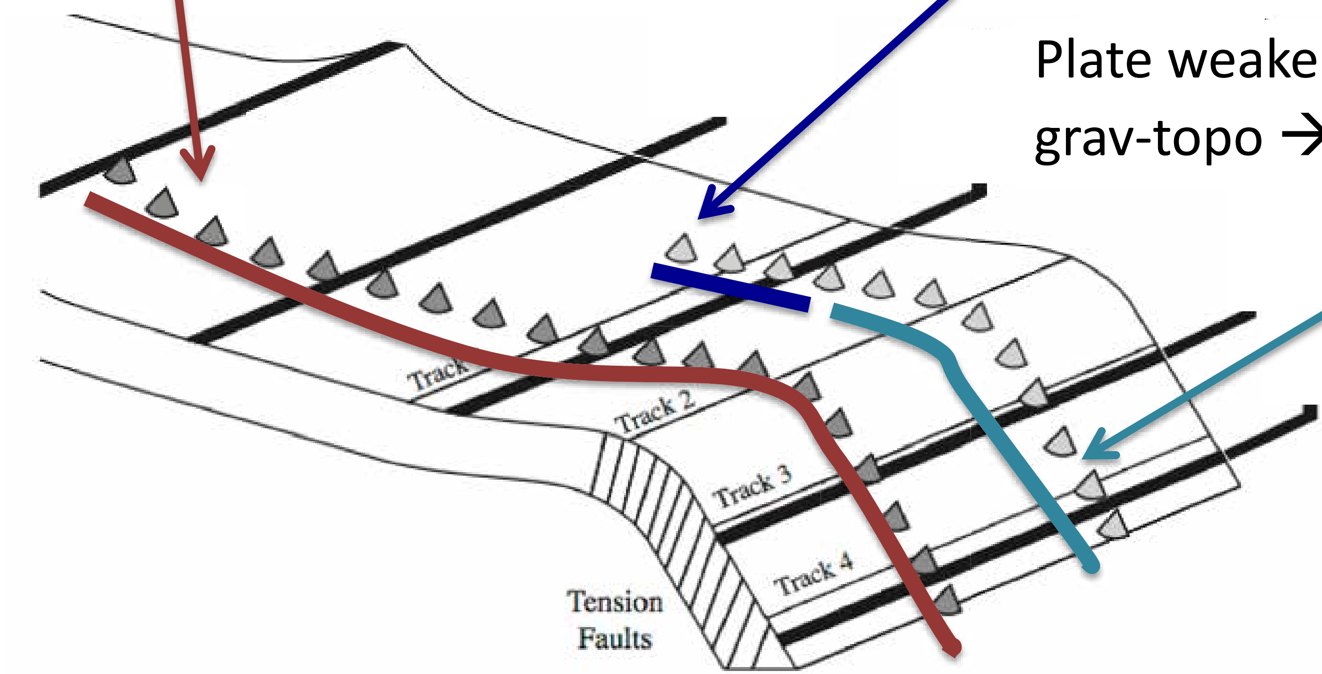
- Use relationship between gravity & topography for an elastic plate to determine effective plate strength along each profile.
- Compare strength along profiles at different distances.

Gravity/Topography measures plate strength

Seamount formed near ridge:
grav-topo → **thin/weak plate**

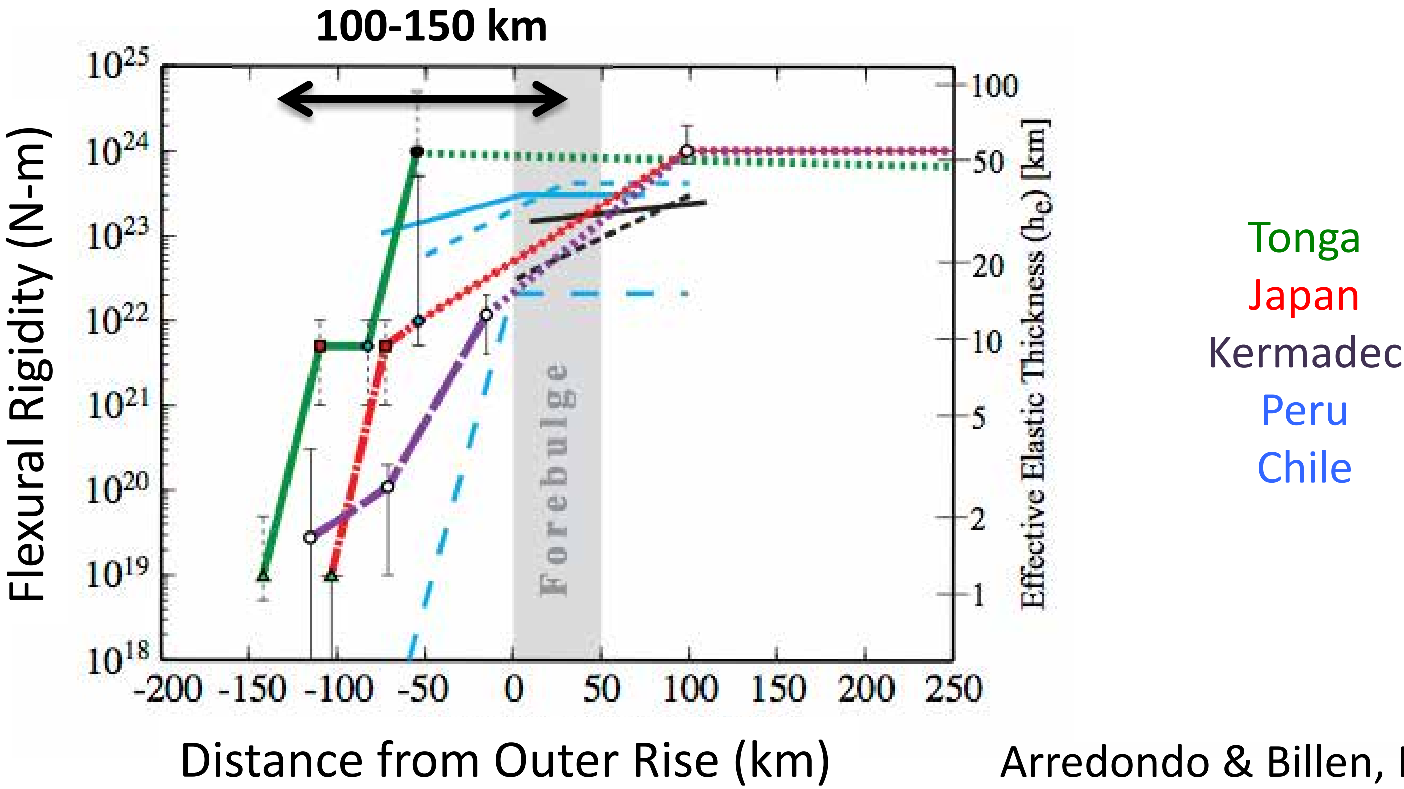
Seamount formed on old plate:
grav-topo → **thick/strong plate**

Plate weakened due to bending
grav-topo → **weak/thin plate**



Arredondo & Billen, PEPI, 2012

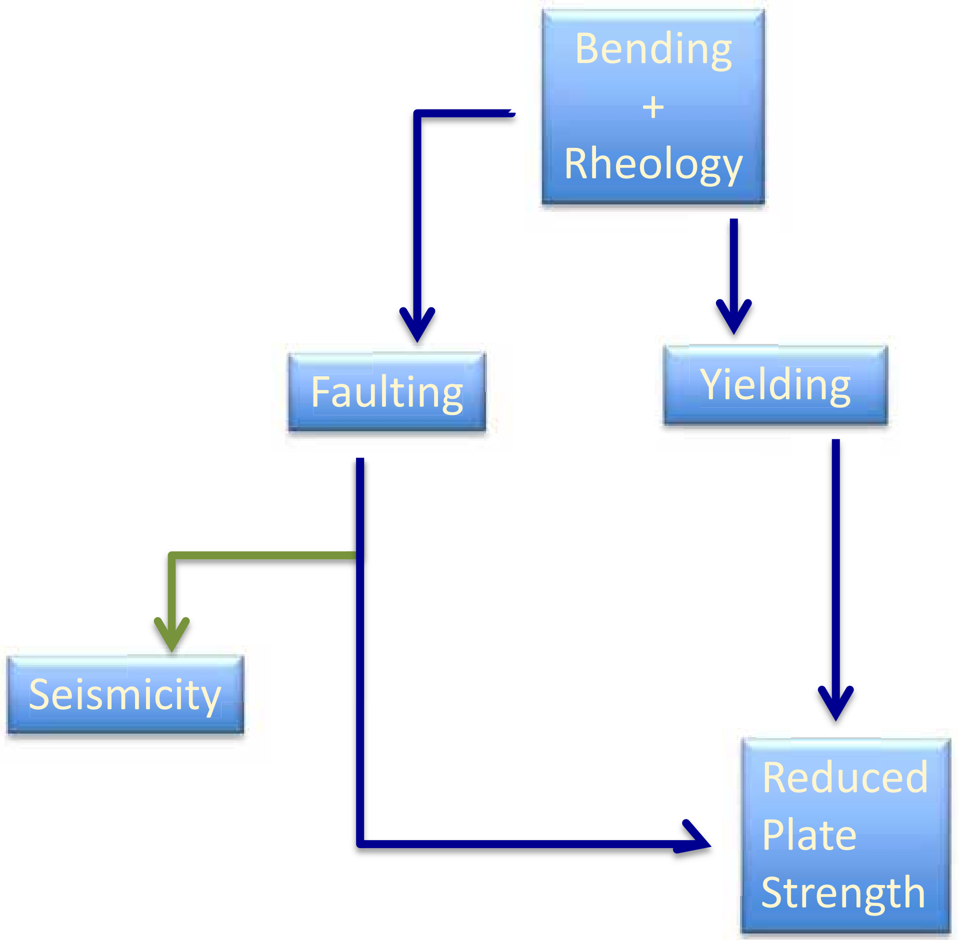
Rapid Weakening of the Subducting Plate



Arredondo & Billen, PEPI, 2012

- Decrease in *flexural rigidity* of 3-5 orders of magnitude.
- Decrease in *elastic plate thickness* from 50 km to < 5-10 km.
- Reduction is evidence of non-elastic behavior
  - **Faulting & plastic yielding throughout the plate**

Deformation Processes in the Incoming Plate from Observations



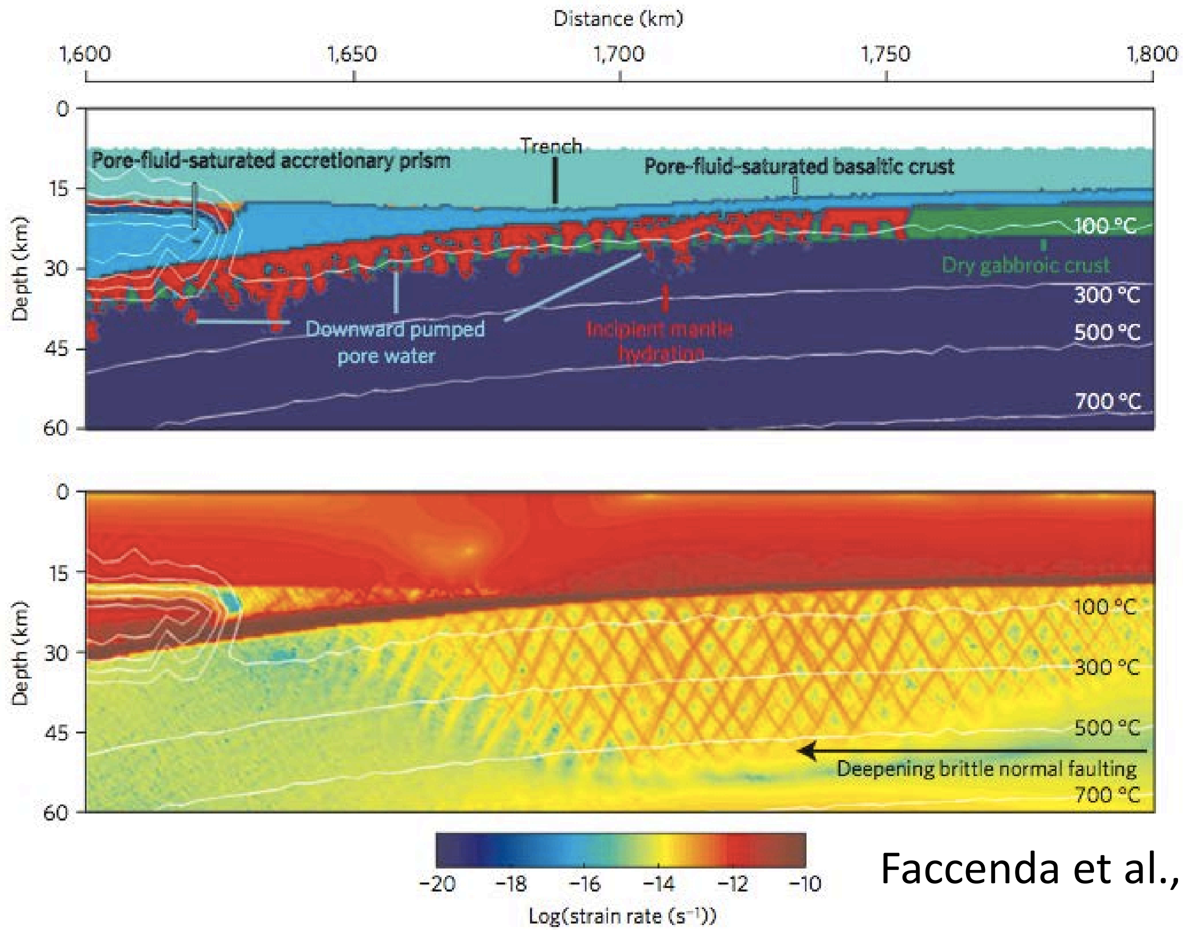
Next step?

Numerical Simulations

- Use observations as constraints

- Test physical relationships between observed deformation and plate strength

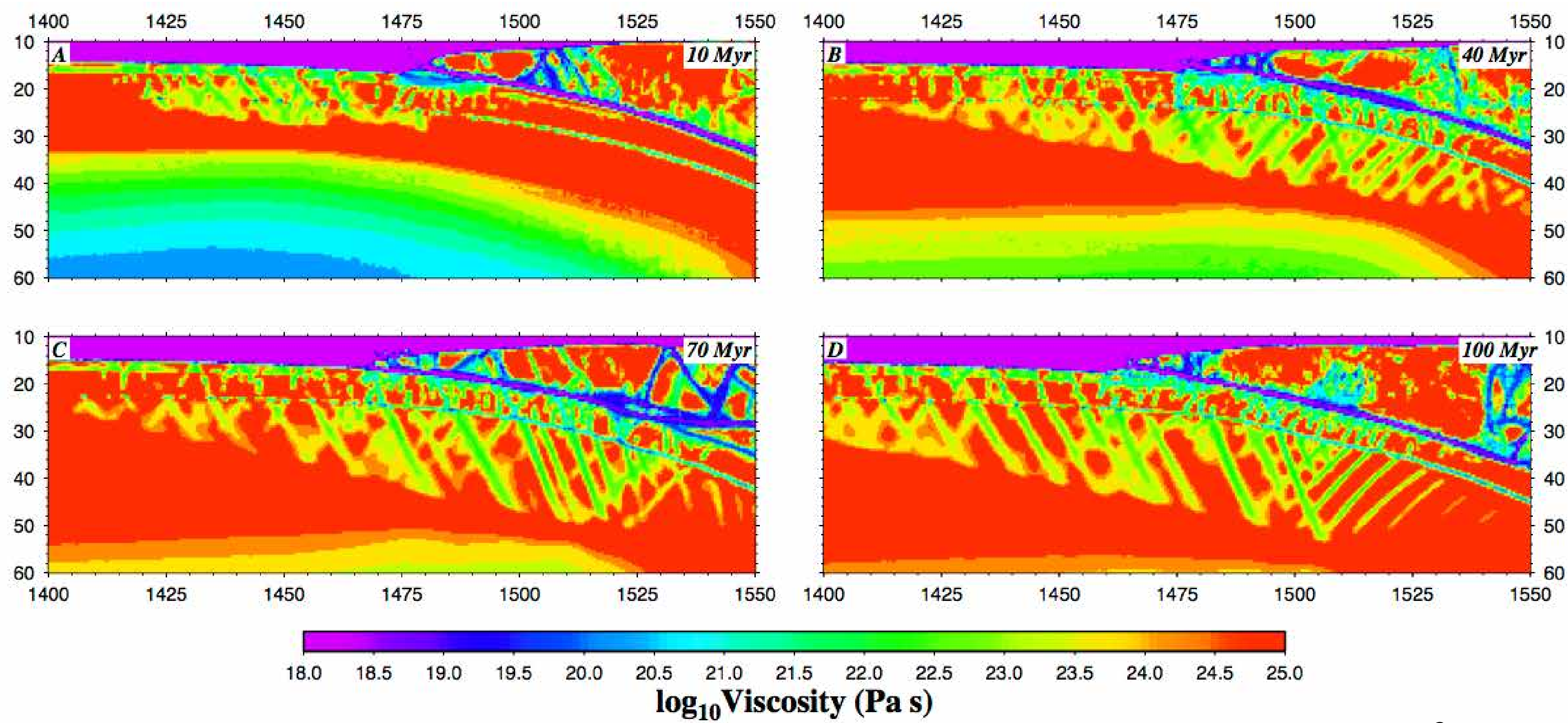
Hydration of the Plate due to Faulting



Faccenda et al., Nature Geo., 2009

- Pressure gradients due to deformation pull water into the plate.
- Fluid flux depends on many parameters including frictional properties of the crust

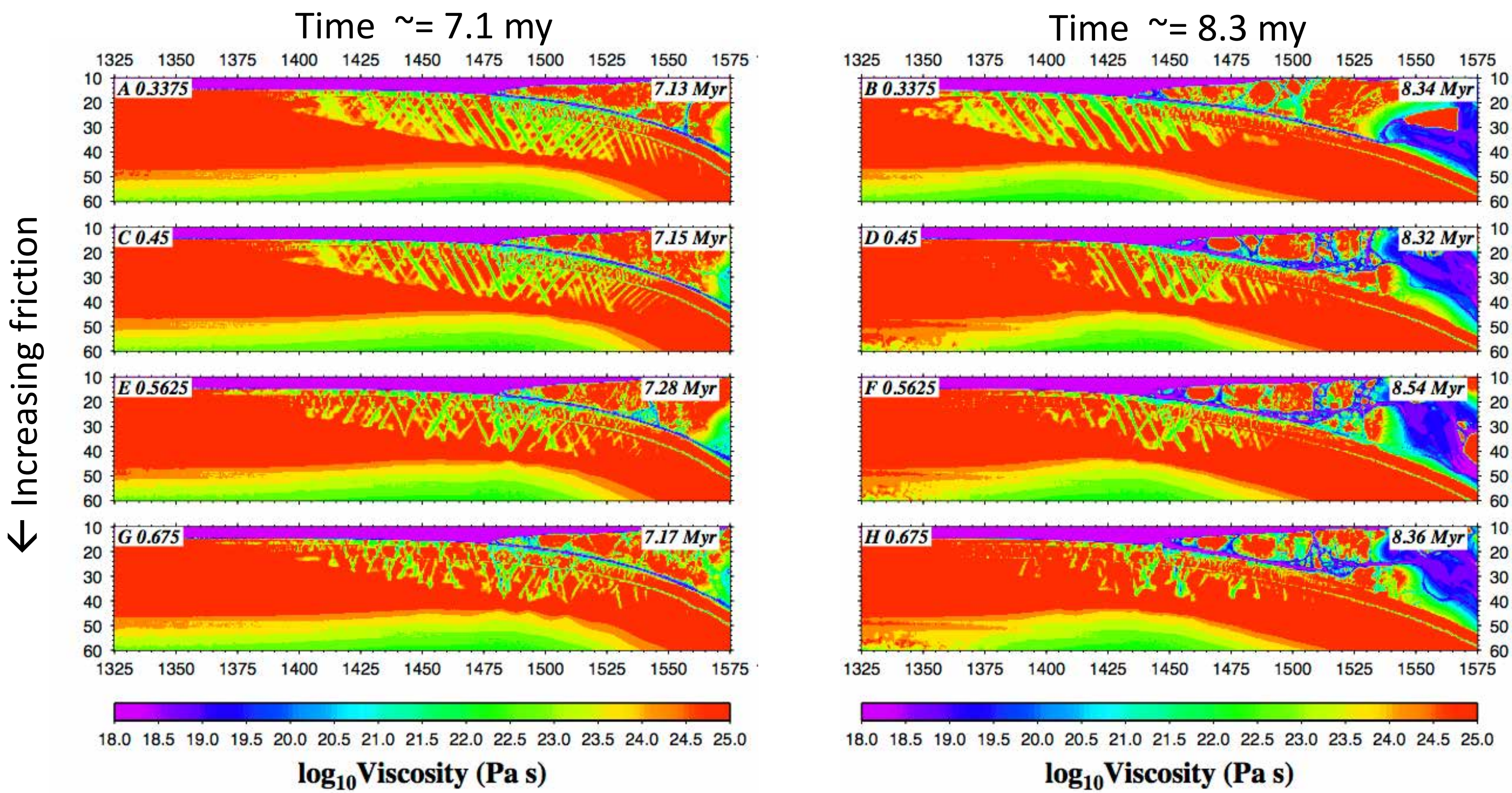
Clear Dependence on Plate Age



Naliboff et al., G[3], 2013

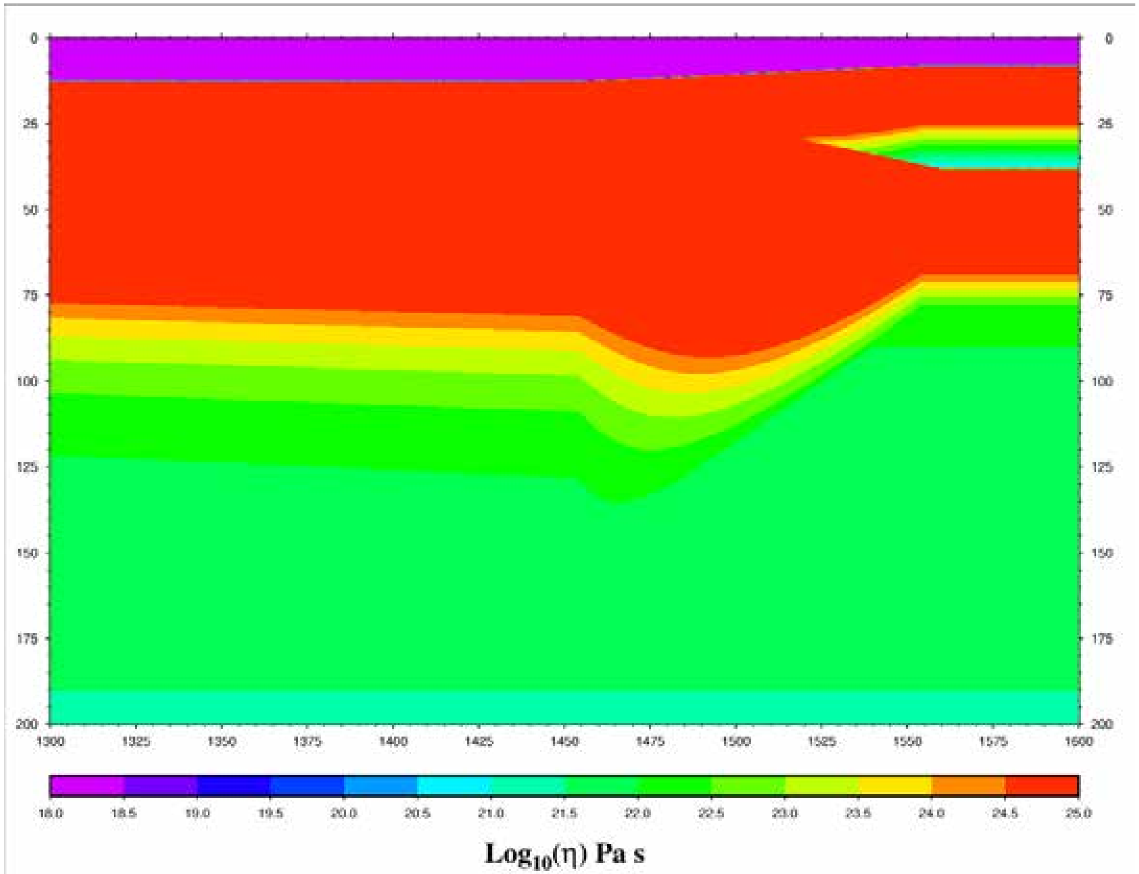
- Younger-to-older plates:
  - Wider region of faulting
  - Faults extend deeper
  - Spacing of faults is roughly constant

Weak Dependence on Fault Friction



- lower friction leads to more faults
- but there's ***more variation*** in a single model ***as a function of time***.

Strong Time-Dependence



Colors:

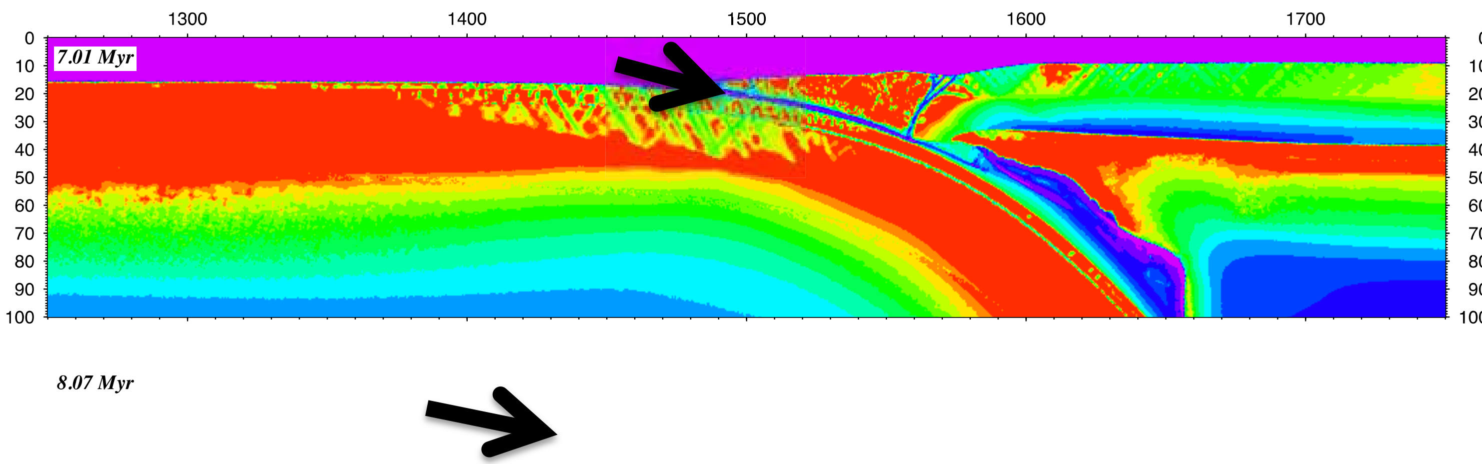
Red is strong (10^{25} Pa-s).

Blue/purple is weak (10^{18}-10^{19} Pa-s).

Naliboff et al., G^3, 2013

- Outer rise fault characteristics vary as plate boundary evolves
  - Width of faulting region
  - Number of faults
  - Fault spacing

Dependence on Plate Boundary Coupling ?

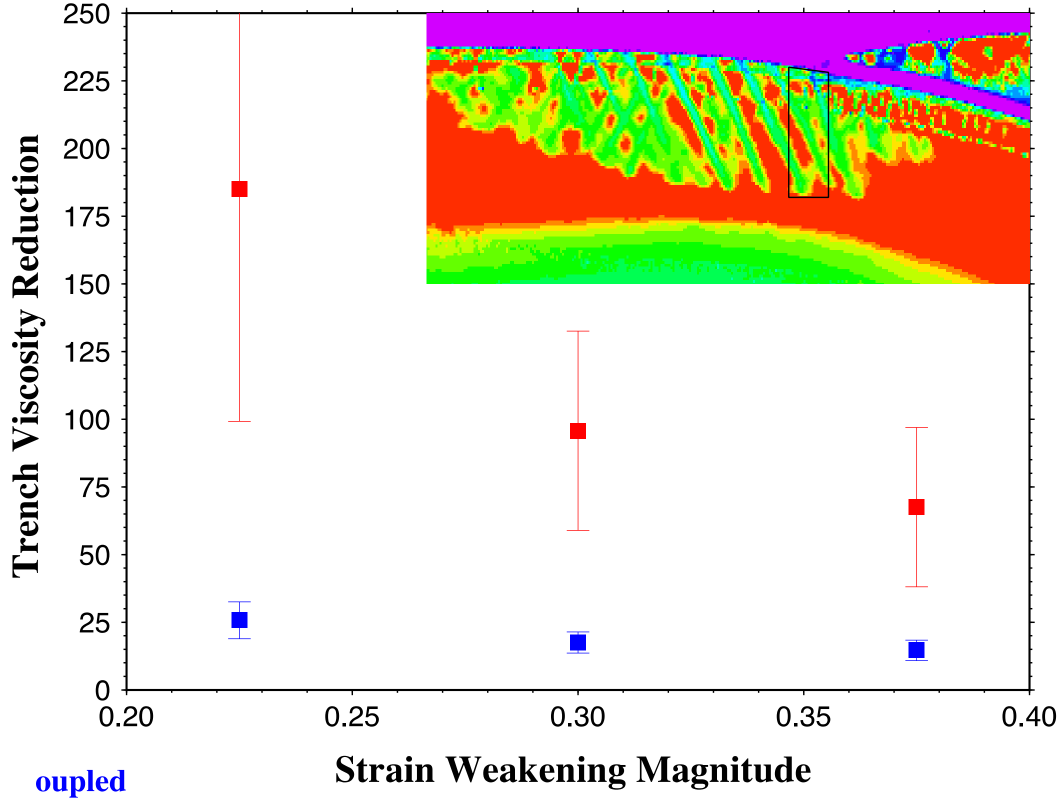


Naliboff et al., G[3], 2013

- PBSZ viscosity decreases by x 10
  - → changes stresses within the slab
  - → Faulting moves seaward.
  - → Slab shape has also changed, but no clear correlation with curvature.

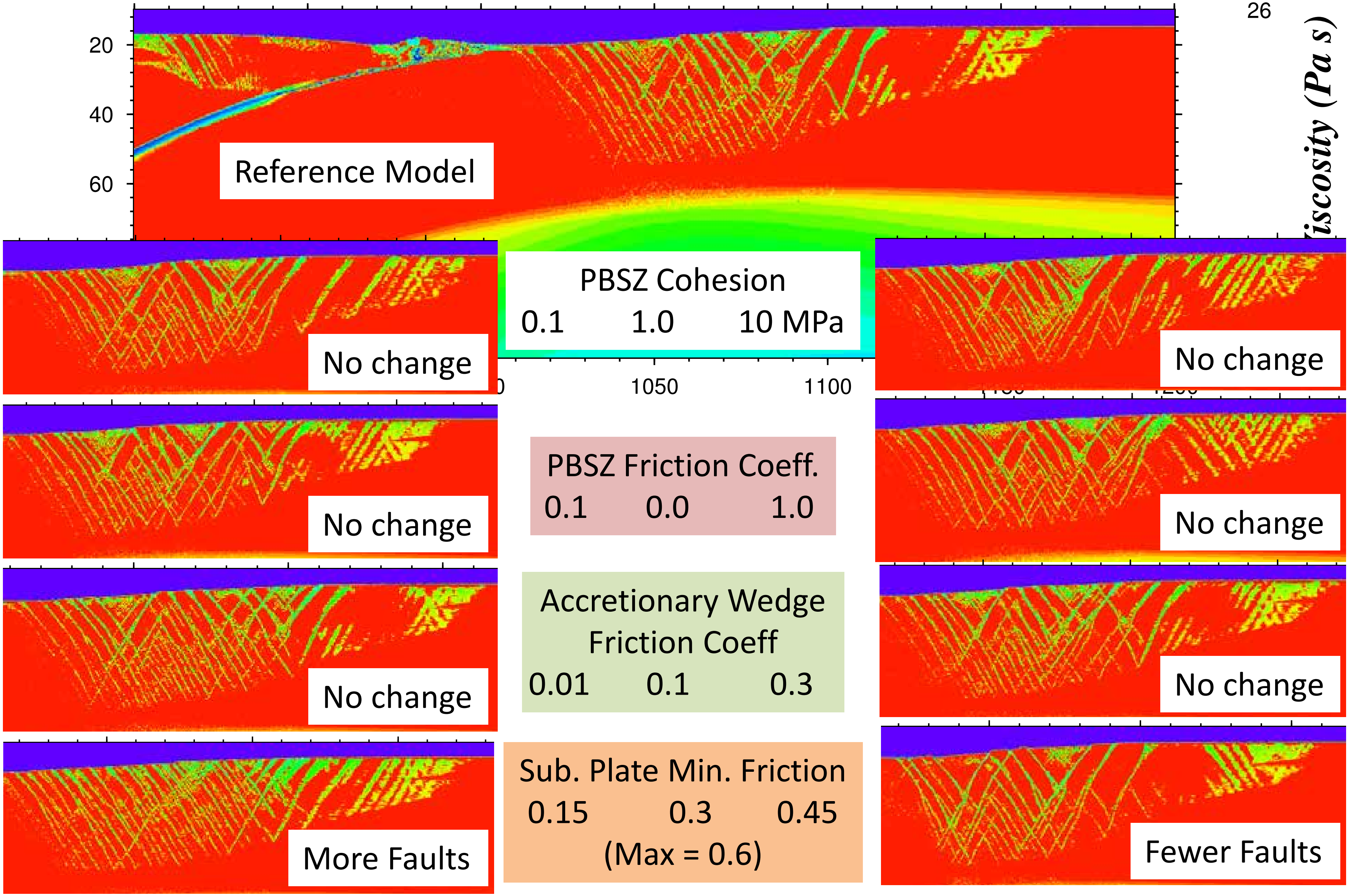
Faulting Weakens Plate *but* Depends on PBSZ

Measure reduction in Plate viscosity at the trench relative to starting plate

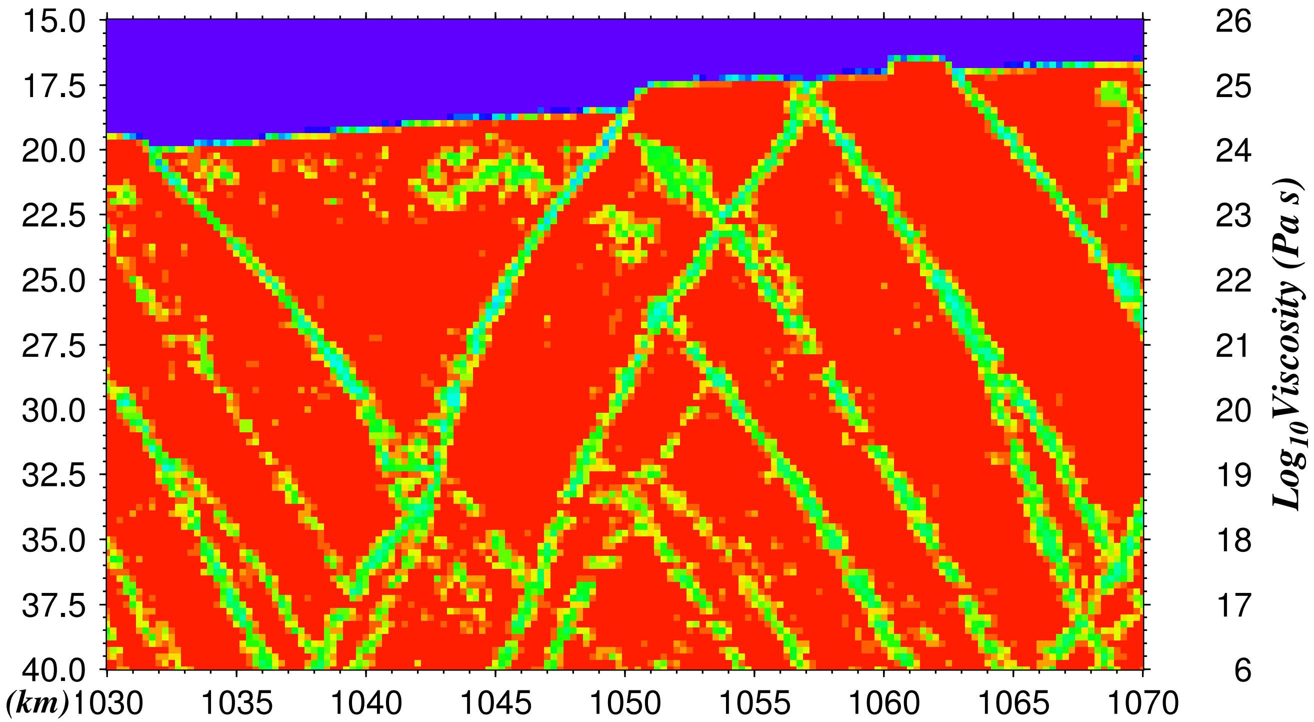


- <u>Coupled interface</u>:
  - 25 times weaker
  - Independent of frictional properties.
- <u>Uncoupled interface</u>:
  - 75-200 times weaker
  - More overall weakening, but less localized.

Instantaneous 2D Tonga Model



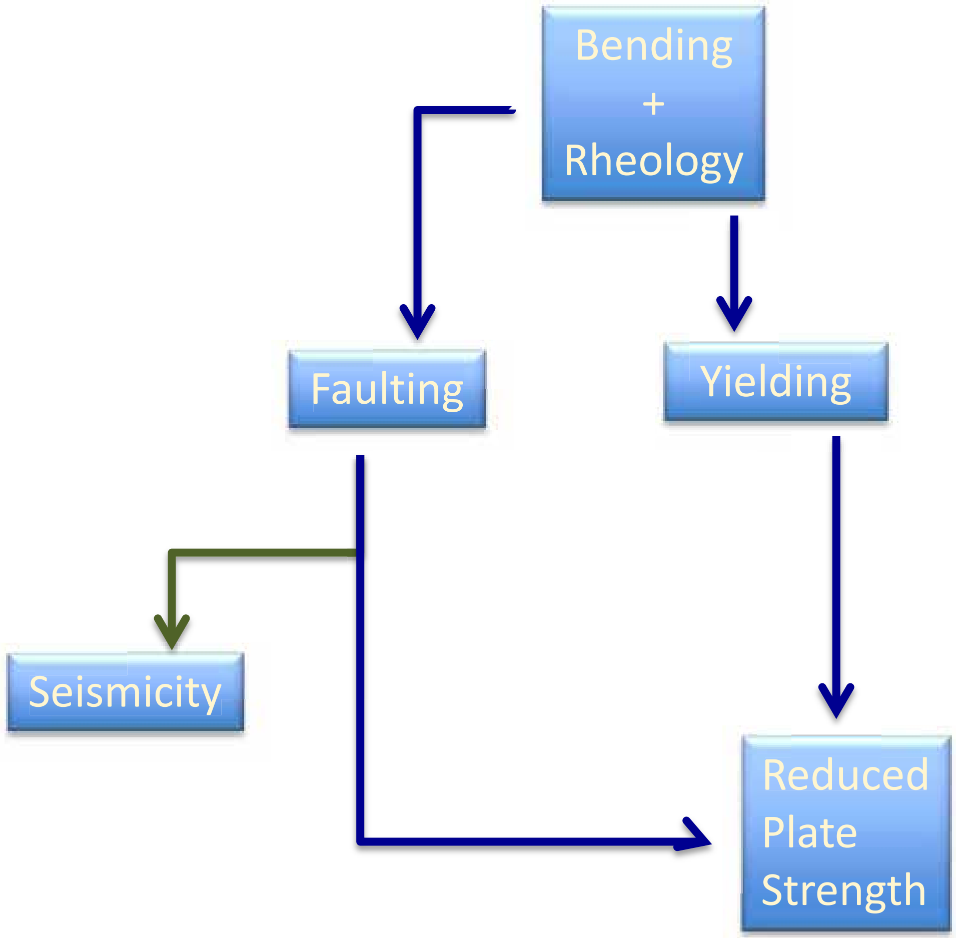
Work in Progress: Compare Fault Characteristics



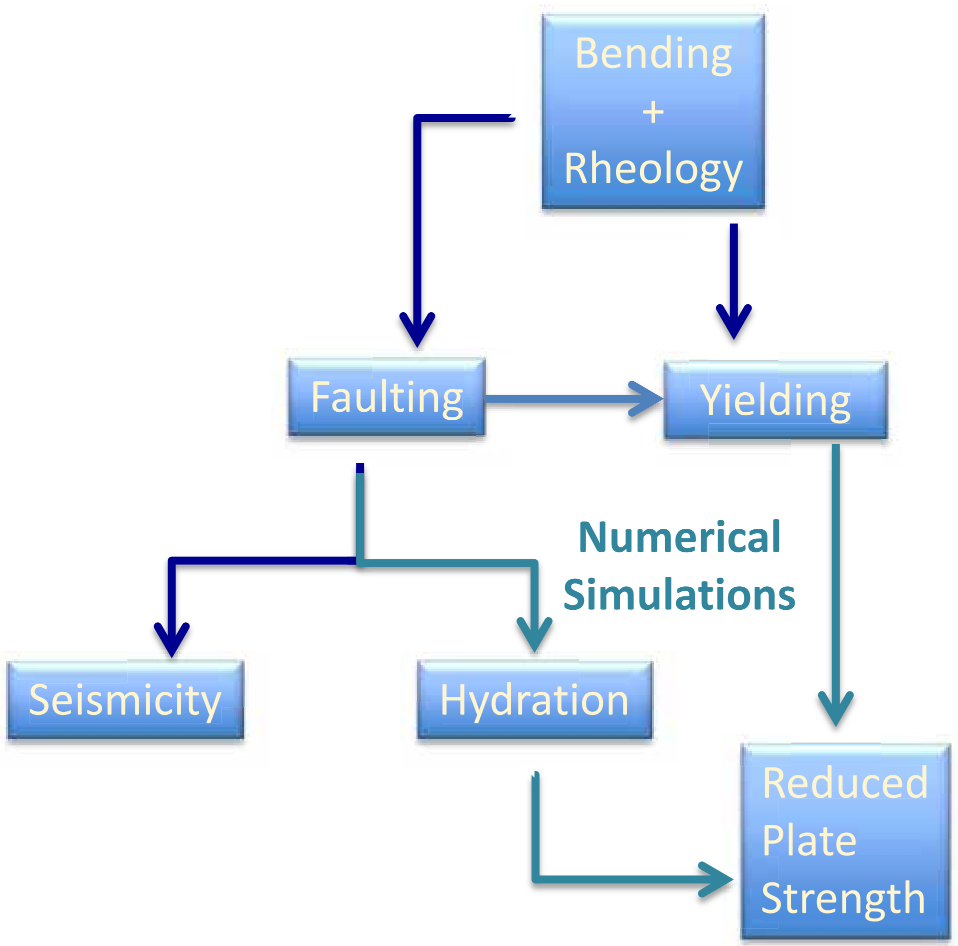
- Effect of water (Tonga models are dry) → PBSZ viscosity & faulting?
- Compare faulting characteristics (spacing, height, direction) to observations.

Deformation Processes in the Incoming Plate from Observations

Before Numerical Simulations



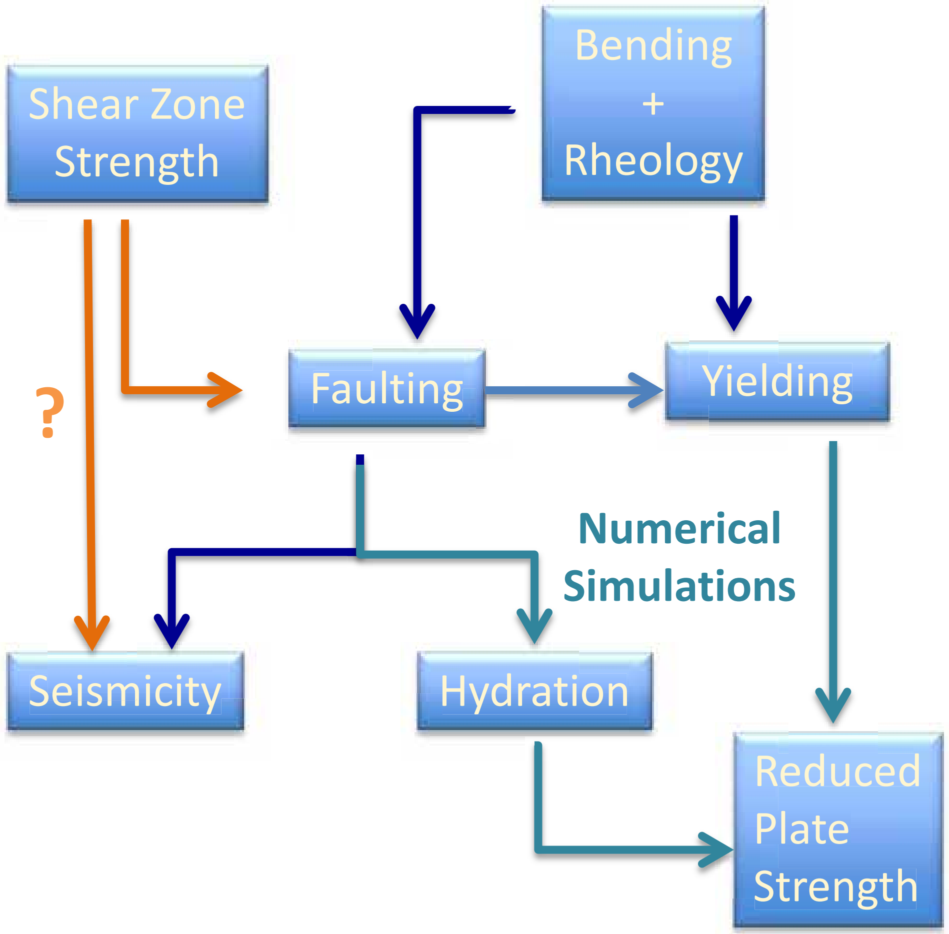
Deformation Processes in the Incoming Plate from Observations & Numerical Simulations



With Numerical Simulations

- Better understand faulting & plate weakening

Deformation Processes in the Incoming Plate from Observations & Numerical Simulations

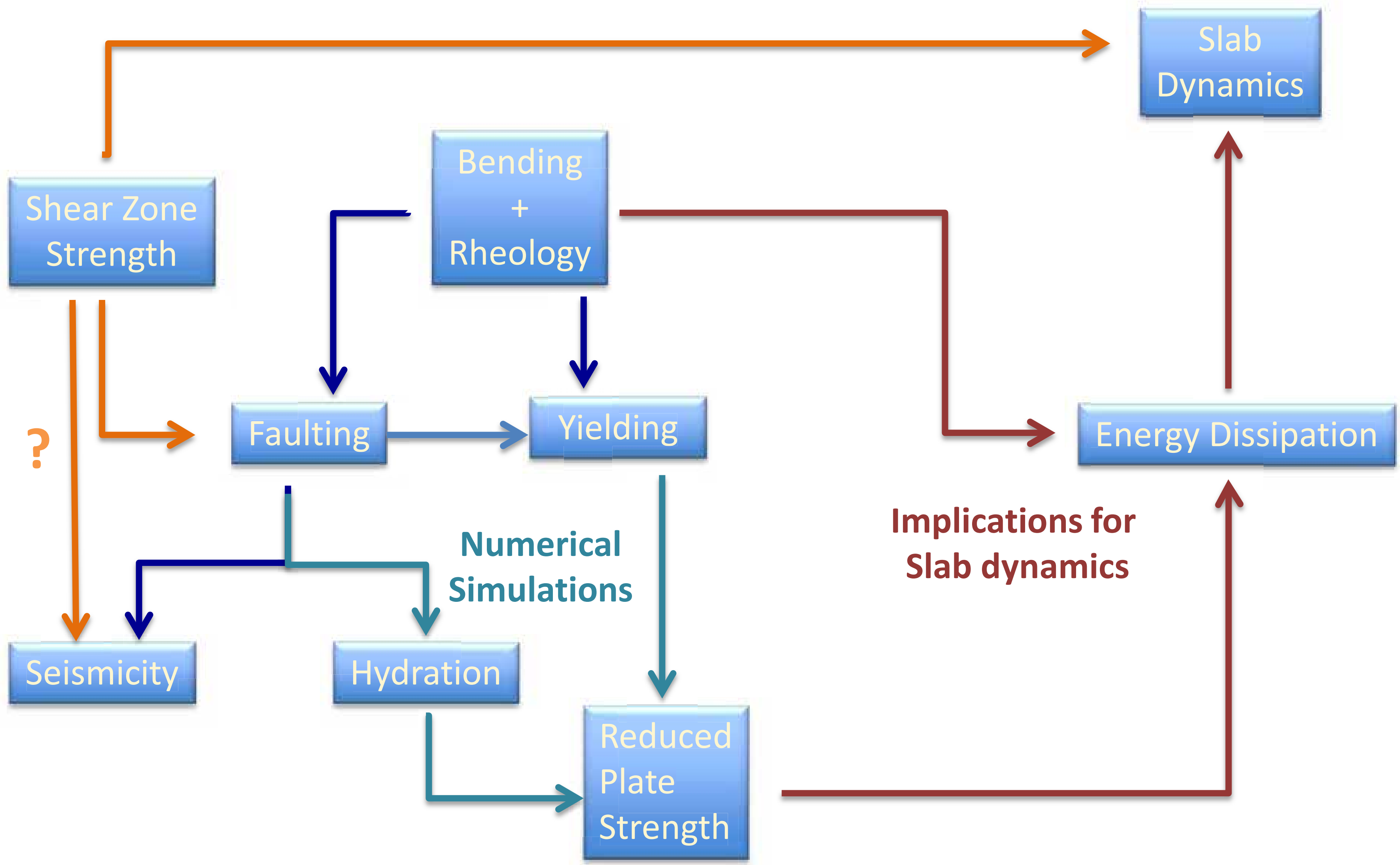


With Numerical Simulations

- Better understand faulting & plate weakening
- Weak dependence on rock frictional properties.
- PBSZ may be important?

- **These processes have implications for slab dynamics.**

Deformation Processes in the Incoming Plate from Observations & Numerical Simulations



Conclusions

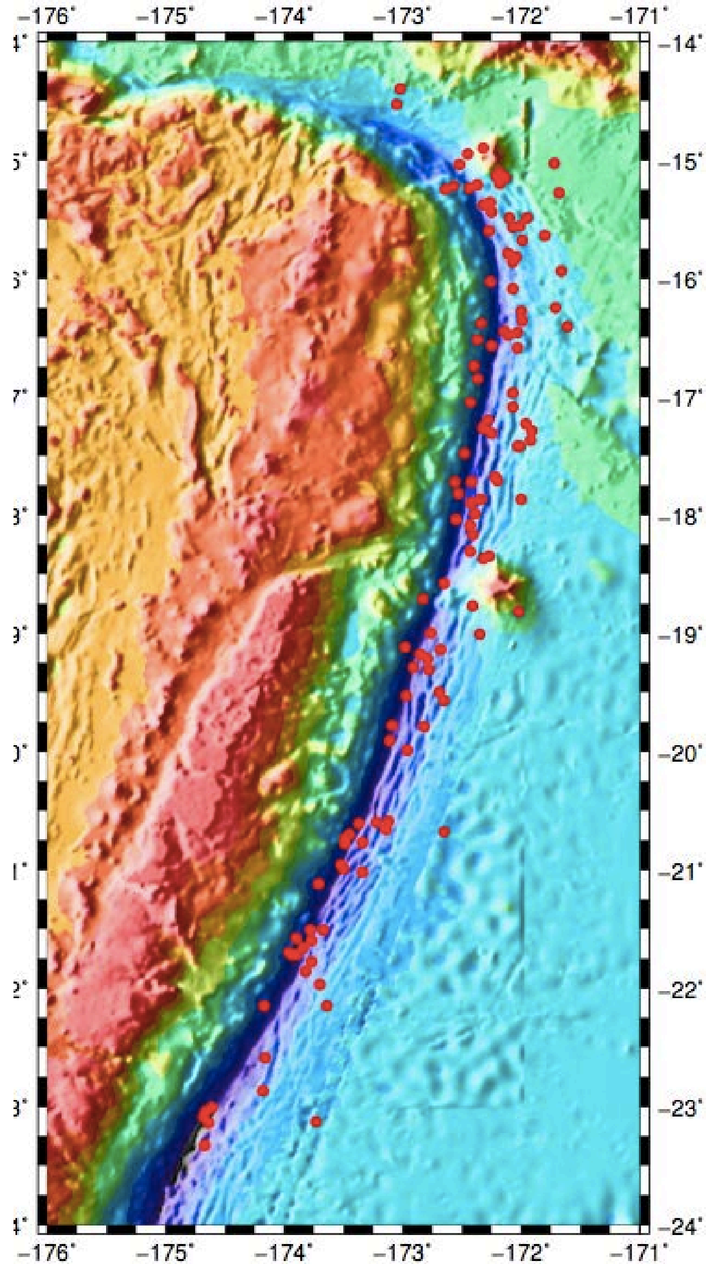
- Observations of outer-rise faulting provides insight into deformation processes of the incoming plate.

- We are in the process of using numerical simulations to more directly link observations to rock properties & bending process.

- Strong time-dependence suggests important feedback between forces & rheology.

Outer-rise Faults are Active Faults

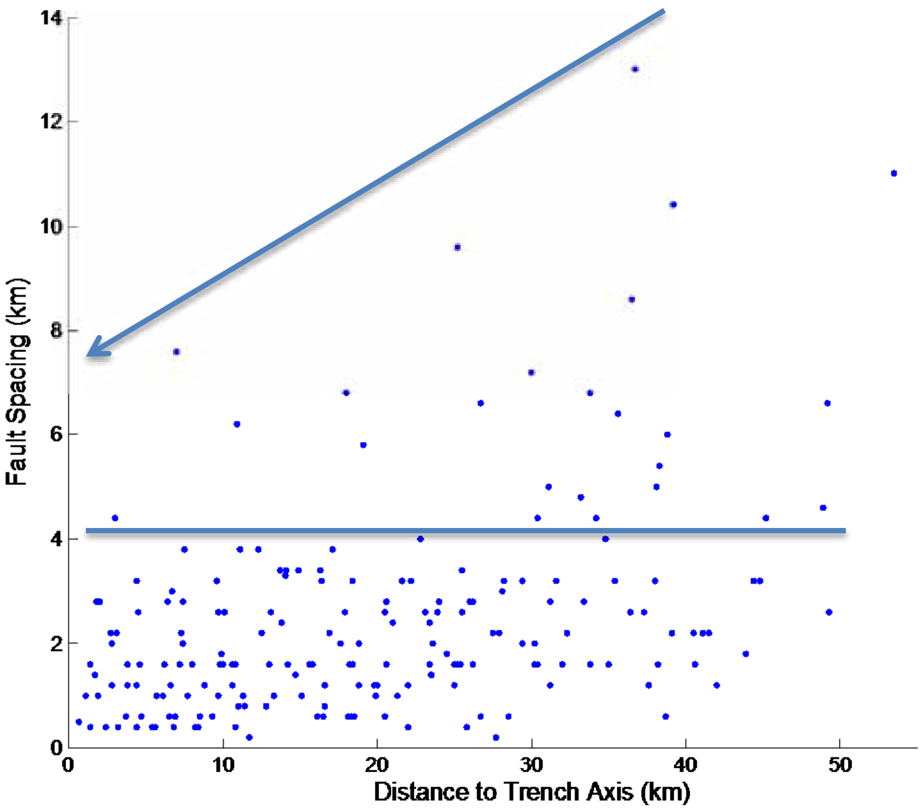
- Seismicity
  - M > 5.0, 1988-2013
  - Some are M > 8.0 (tsunami-genic)
- Large events cut through much of the plate (> 30 km)
- Exhibit some relation to mega-thrust events (preceding or following)
  - May reflect stress transfer

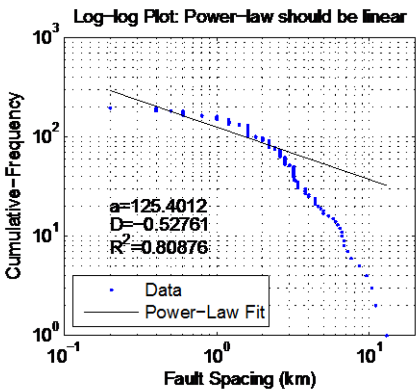


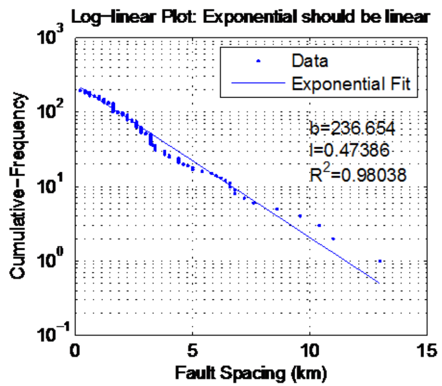
Insights from Analogue Experiments

- Stretching: faults form simultaneously and are distributed throughout the stretching region.
  - at low strain, elastic interaction, unconstrained growth of faults, leads to a power-law N(s) for fault length and spacing.
  - As strain increases, fault growth is constrained by the layer thickness and elastic interaction becomes less important, leads to a exponential-law N(s)) for fault length and spacing.
  - Transition occurs at higher strain for thicker layers. Ackerman et al., 2001
- Flexing differs because faults form sequentially along the bending axis, they therefore move from a high strain-rate region to a lower strain-rate region as they accumulate strain.
  - N(s) is less clear for length (neither model fits), but for spacing it is better fit by an exponential-law. Spacing is anti-clustered.
  - Sequential growth inhibits elastic interactions between faults.
  - Length-scale is not clearly related to plate thickness. (Supak et al., 2006)

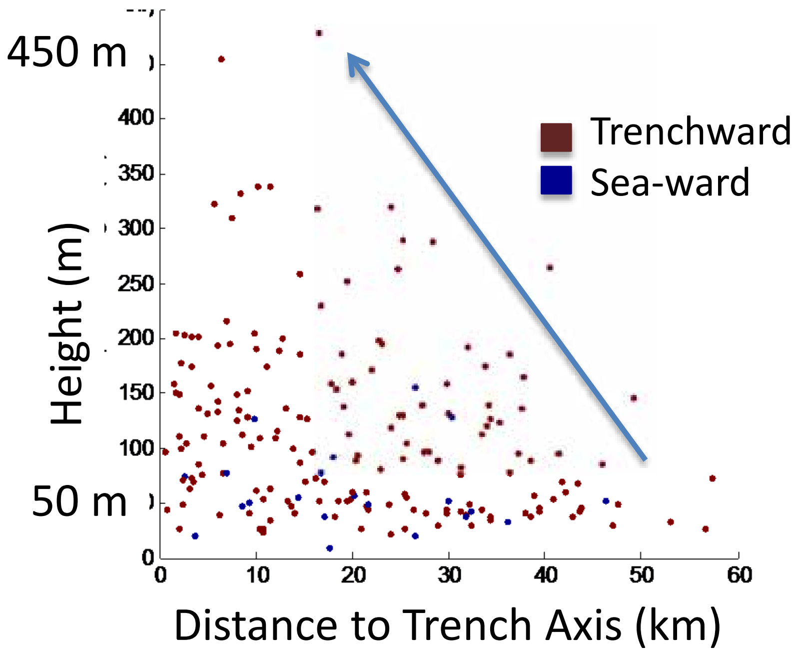
2. Faulting Characteristics: Tonga

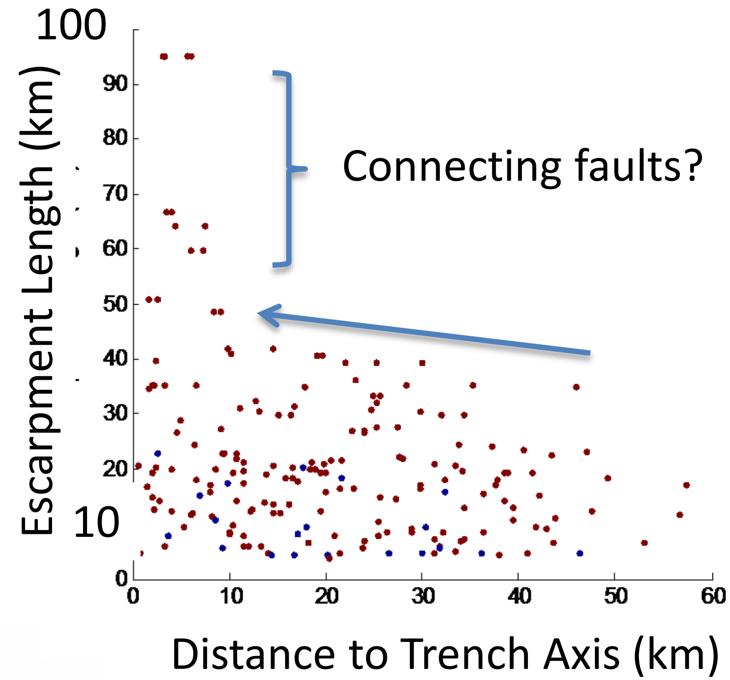


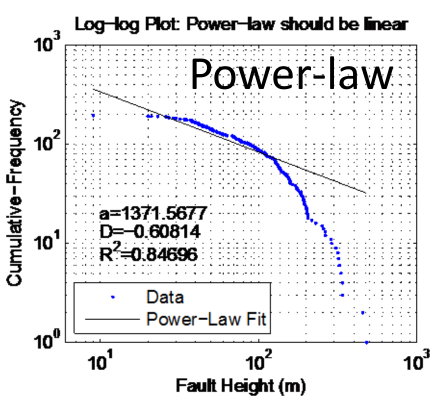


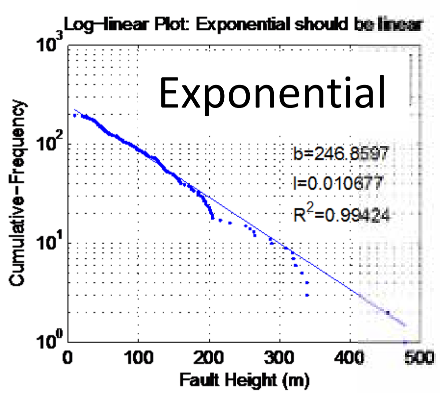


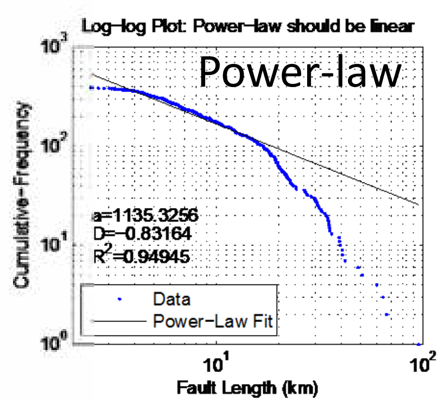
2. Faulting Characteristics: *Costa Rica*

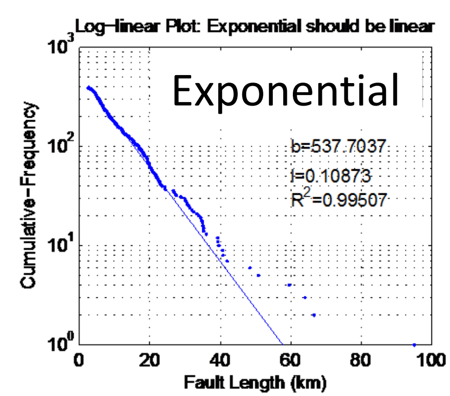






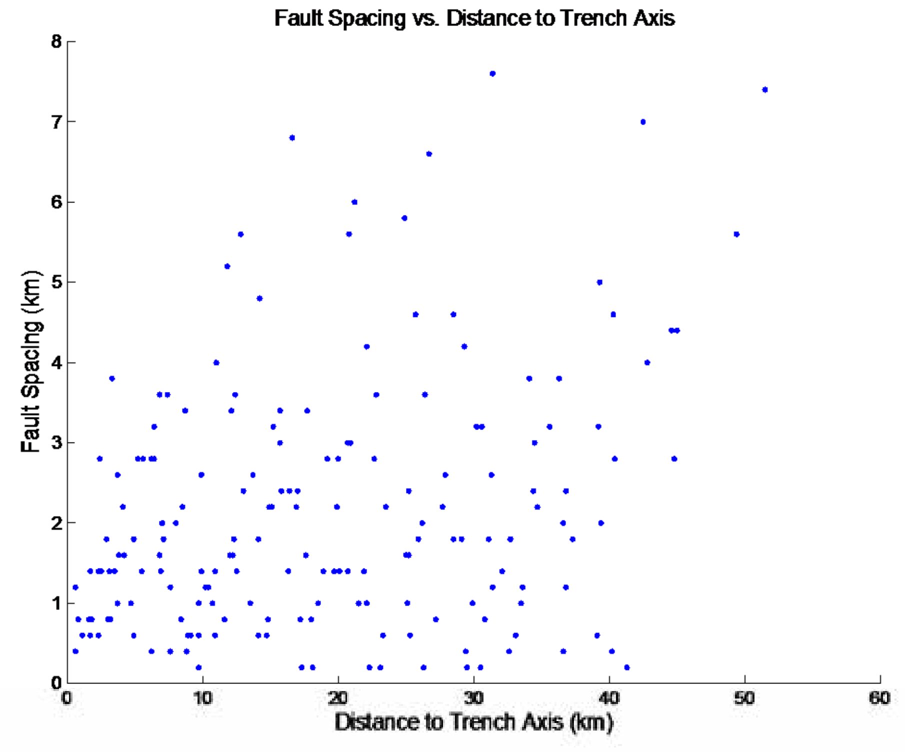


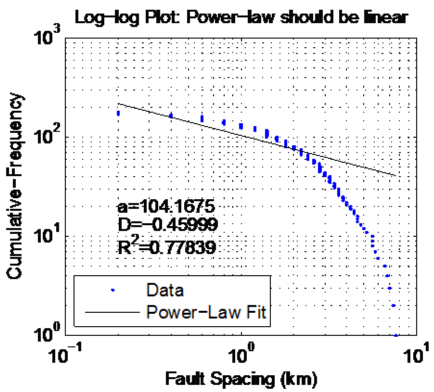


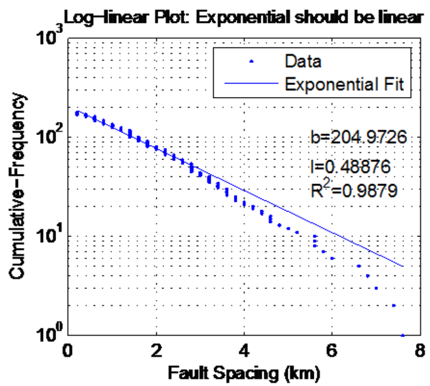


- Data is better fit by an exponential.

2. Faulting Characteristics: Costa-Rica







Conclusions: from Observations

- Rapid reduction in plate strength occurs between the outer rise and the trench
- Outer rise faults form in "normal" oceanic crust with no significant pre-existing reduction in frictional properties.
- Size-frequency characteristic of outer rise faults follow an exponential law;
  - physical interpretation of length-scale is not clear.
  - may be related to width of high strain-rate zone at bending axis.

Conclusions: From Simulations

- Formation of outer-rise faults arises from a cohesion/friction-loss rheology
- Pressure gradients within outer rise faults pull sea-water into the subducting plate. (Faccenda et al., 2009).
- Region of faulting is broader/deeper for older subducting plate age.
- More friction-loss (lower min) within subducting plate leads to fewer faults with large fault offsets, and vice versa.
- Other rheologic variations have little or no affect on fault characteristics.
- Fault Characteristics <u>are</u> time-dependent: changes in BC (slab pull, horizontal extension/compression).

2. Faulting Characteristics

	Mid-Amercia	Western Kuriles	Tonga
Age (my)	24 - 28	120-128	105-115
Overriding Plate	Continental	Continental	Oceanic
New/Reactivated	Reactivated	Reactivated	New
Sub. Velocity (mm/y)	58	39	113
Shallow Dip (mean)	29-32	24-27	35-38
Characteristic Height (m)	93.6	43.7	258.4
Characteristic Length (km)	9.2	6.1	16.1
Characteristic Spacing (km)	2.0	2.9	2.1

Saunders, Billen, Naliboff, unpublished

- **Tonga** has longest faults with largest offsets, but low fault spacing.
- **All regions have similar fault spacing.**