Earthquake Source Physics at various depths
Energy Budget and Scaling

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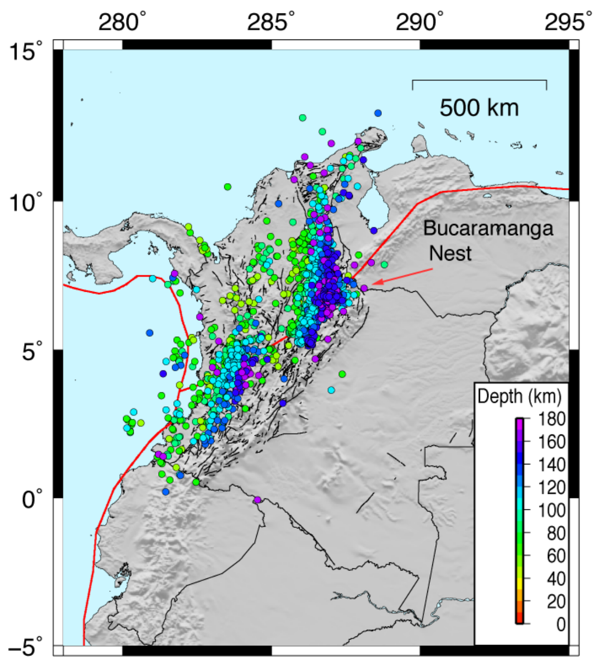
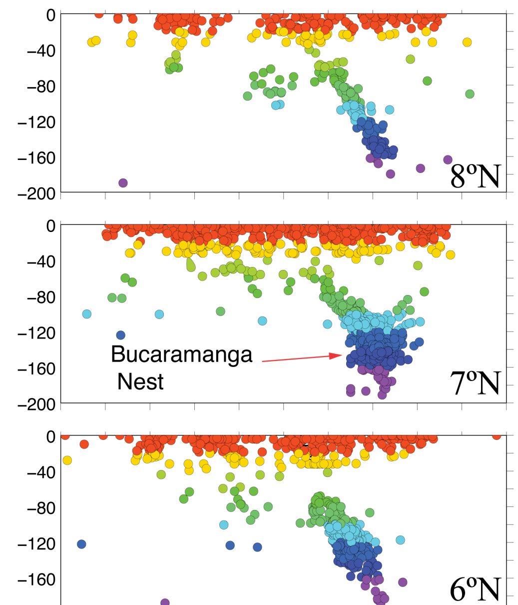


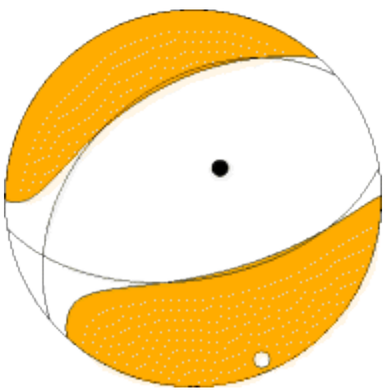


October 3, 2012
Earthquake Source Physics Workshop
ECGS, Luxembourg

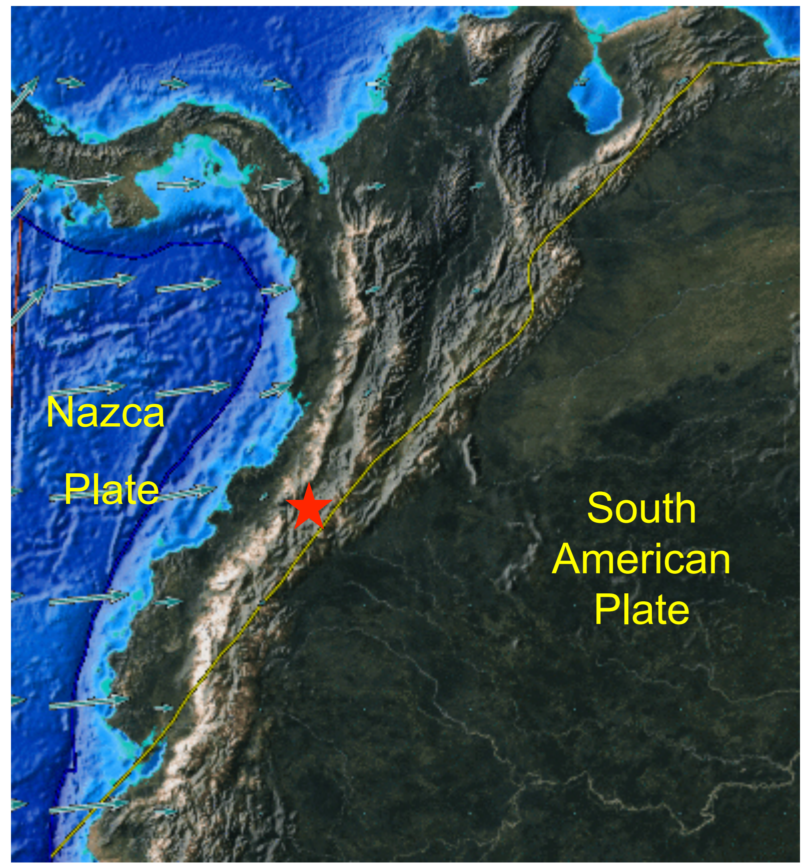
Magnitude 7.3 COLOMBIA
Sunday, September 30, 2012 at 16:31:35 UTC

Based on it's depth and nature, this earthquake occurred within the subducting Nazca Plate. The Nazca plate, oceanic in origin, subducts beneath the South American plate along the South America trench.

At the location of this event, the Nazca plate moves east-northeast with respect to the South American plate at a rate of approximately 60 mm/yr.



USGS Centroid Moment Tensor Solution



UNAVCO

IRIS
Teachable Moments

Magnitude 7.3 COLOMBIA
Sunday, September 30, 2012 at 16:31:35 UTC

The earthquake (blue star) is plotted with epicenters of earthquakes in the region since 1990. It occurred at a depth of 168.3 km (104.6 mi).

Earthquakes on the subduction zone boundary are shallow near the trench and become deeper toward the east-northeast as the Nazca Plate descends beneath Ecuador and Colombia.

According to the USGS, deep earthquakes in this region of the Nazca plate are not uncommon; there have been 13 similar events deeper than 100 km over the past 40 years, within 500 km of this earthquake.

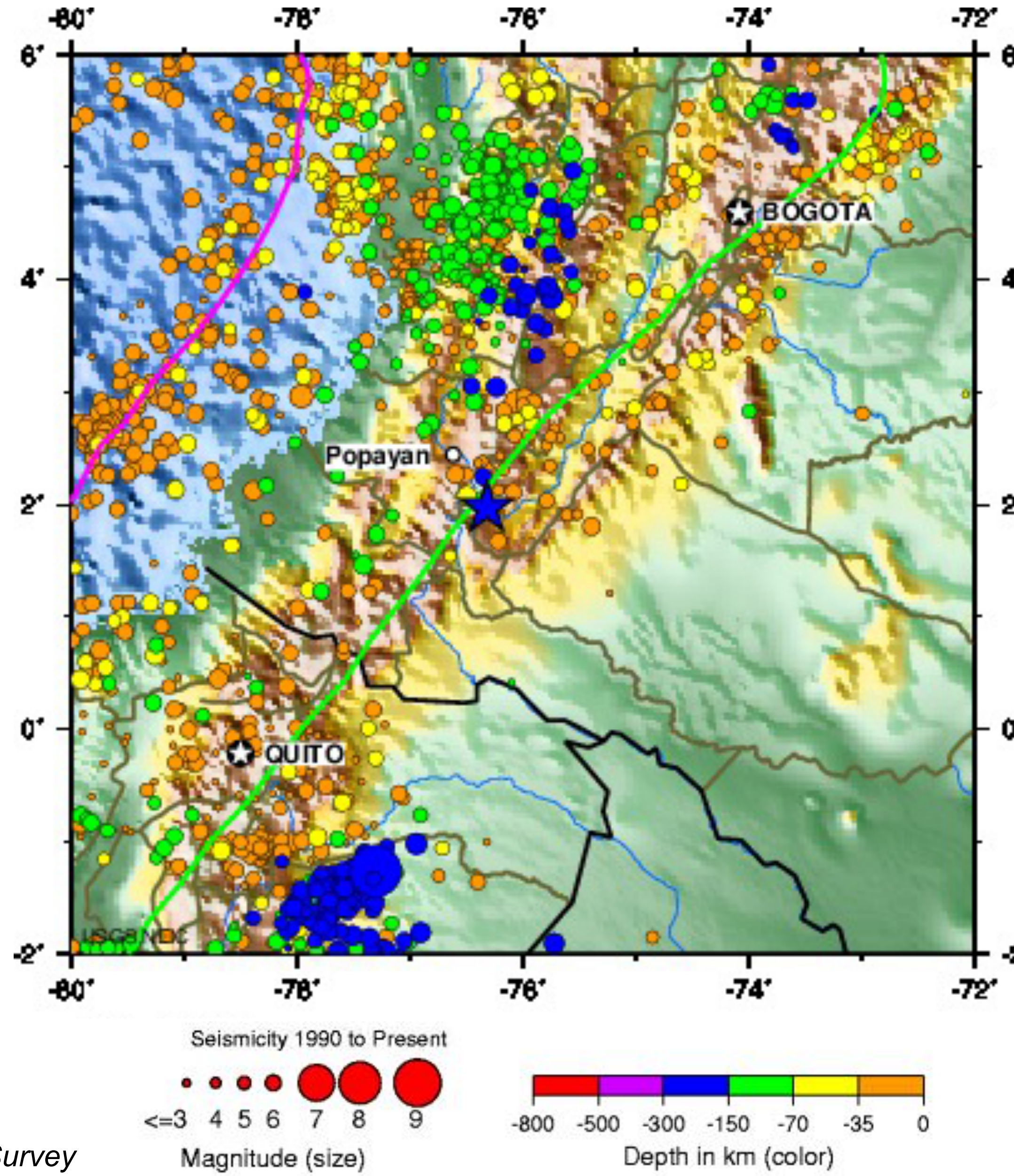
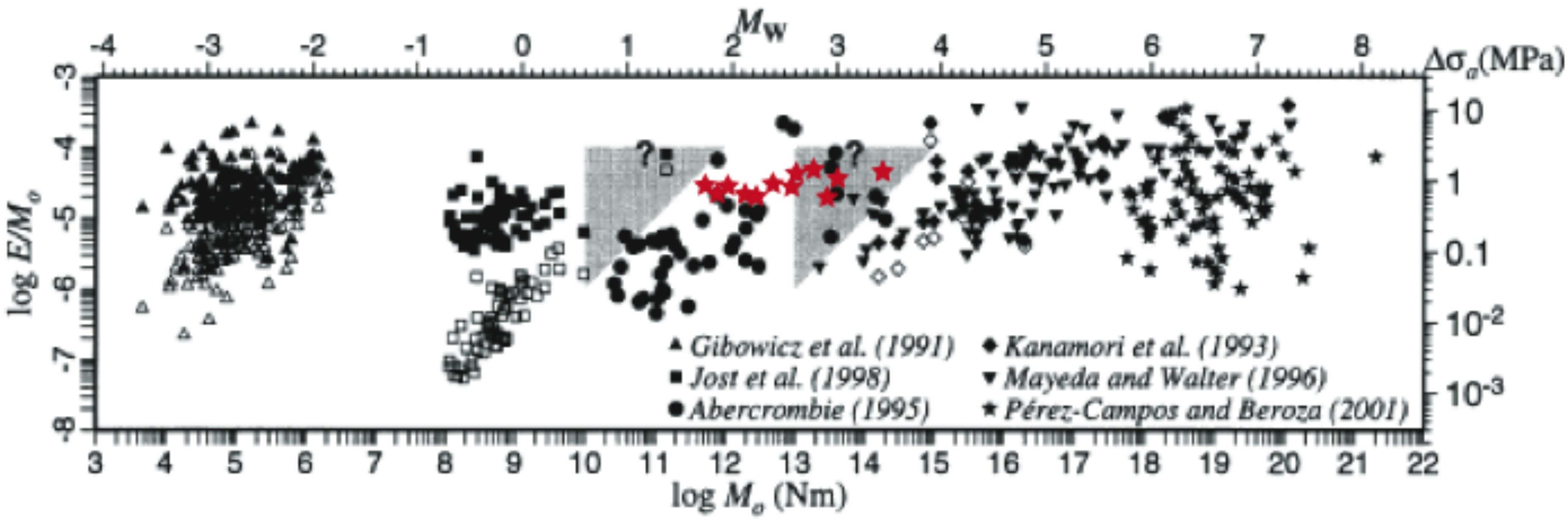


Image courtesy of the US Geological Survey

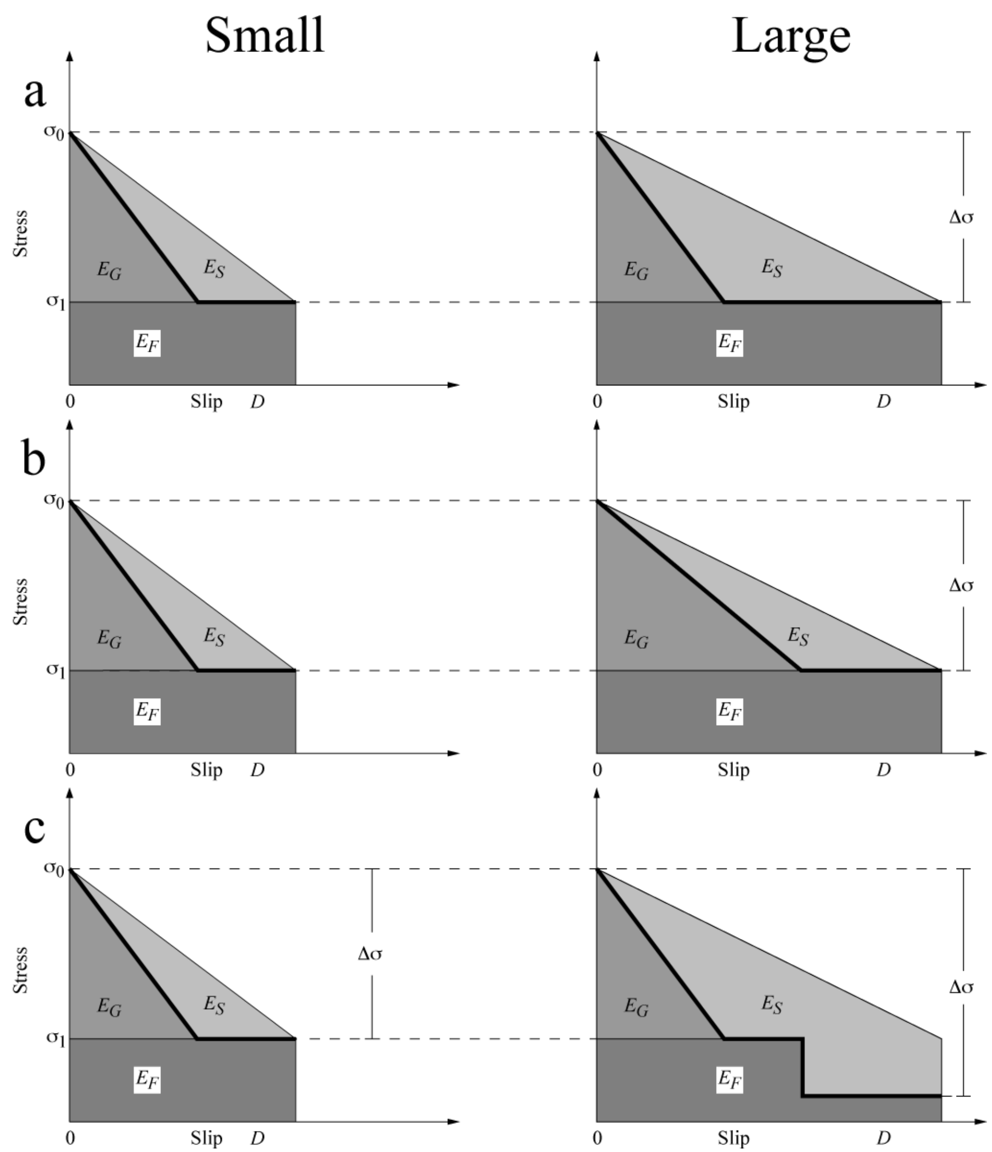
Energy Budgets and Scaling Issues

IDE AND BEROZA: DOES APPARENT STRESS VARY WITH EARTHQUAKE SIZE? 3351



$$\sigma_a = \mu \frac{E_S}{M_0} = \frac{E_S}{AD}$$

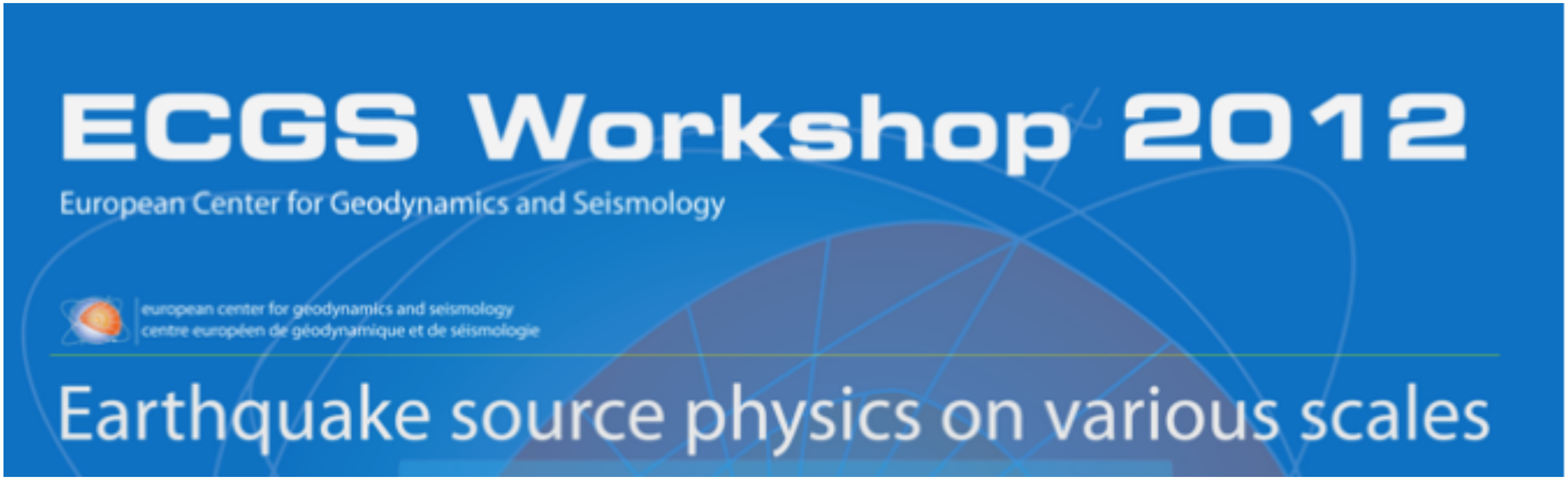
Energy Budgets and Scaling Issues



All the terms **scale with** earthquake **size** (Aki, 1967)

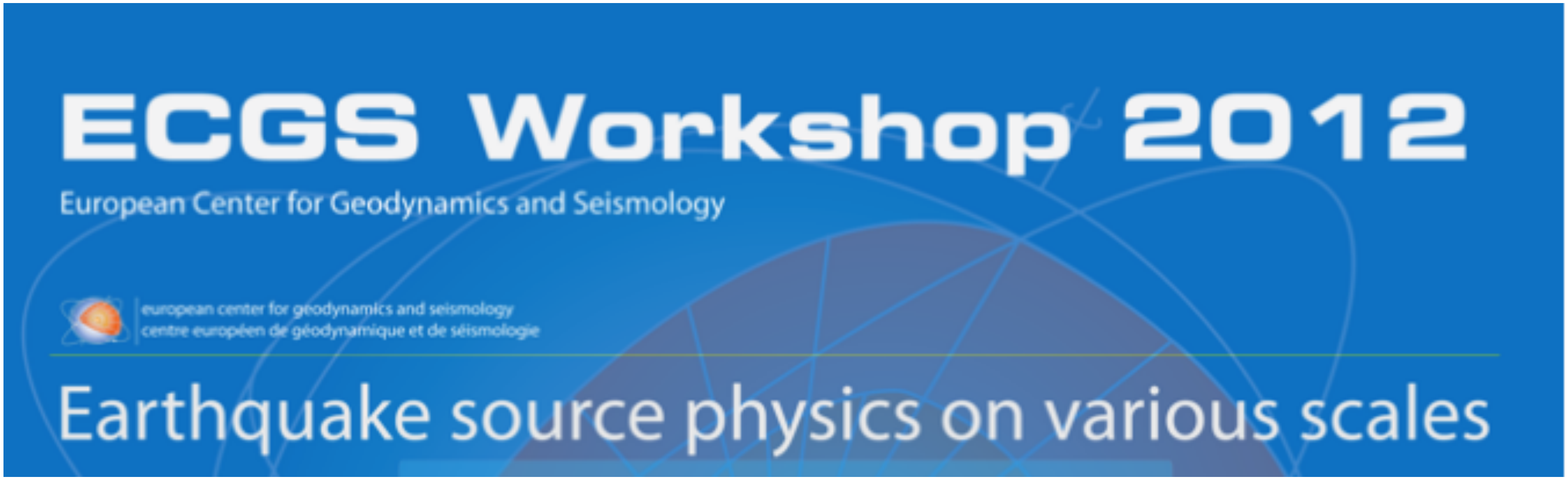
$$\sigma_a = \mu \frac{E_S}{M_0} = \frac{E_S}{AD}$$

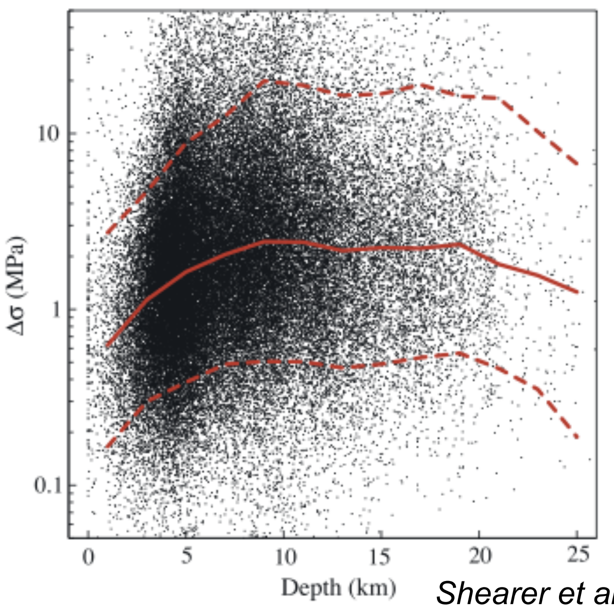
Earthquake Source Physics at depth



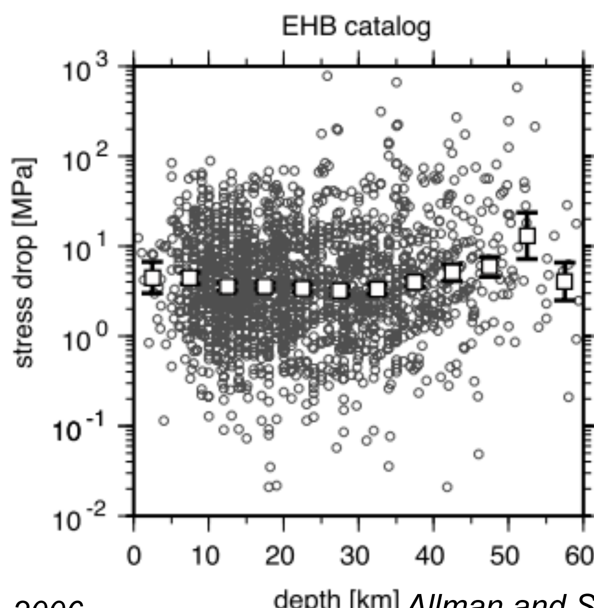
What about Depth?
Does EQ behavior change as a function of depth?

Energy Budgets and Scaling Issues





Shearer et al., 2006



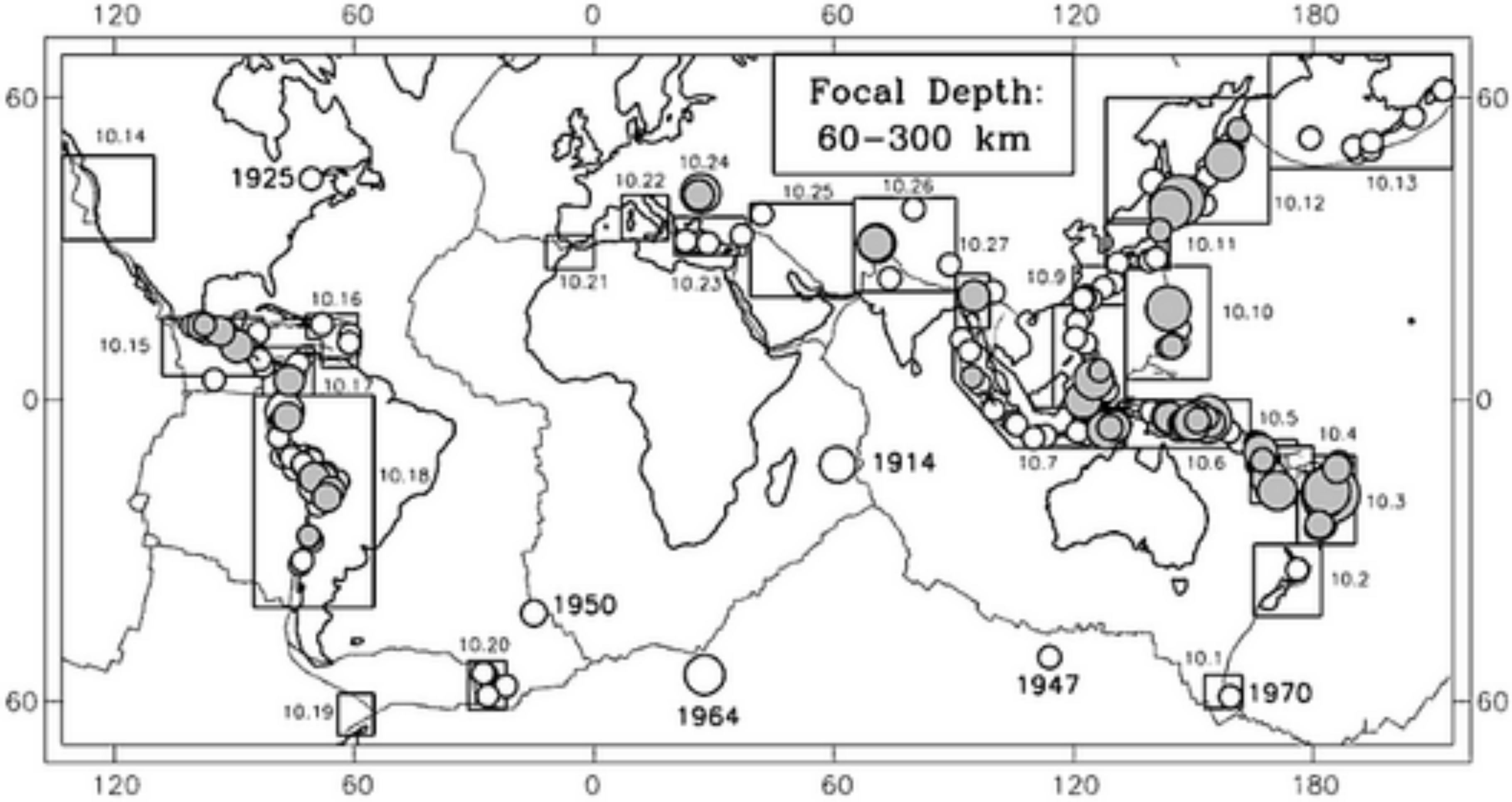
Allman and Shearer, 2009

What happens beyond 50+ km. depth?

Deep and Intermediate Depth Earthquakes

Depth > 50 – 60 km

Intermediate Depth Earthquakes



Deep and Intermediate Depth Earthquakes

Depth > 50 – 60 km

25% of global earthquake catalogs

Mechanism is not well constrained

Intermediate Depth Earthquakes

Deep and Intermediate Depth Earthquakes

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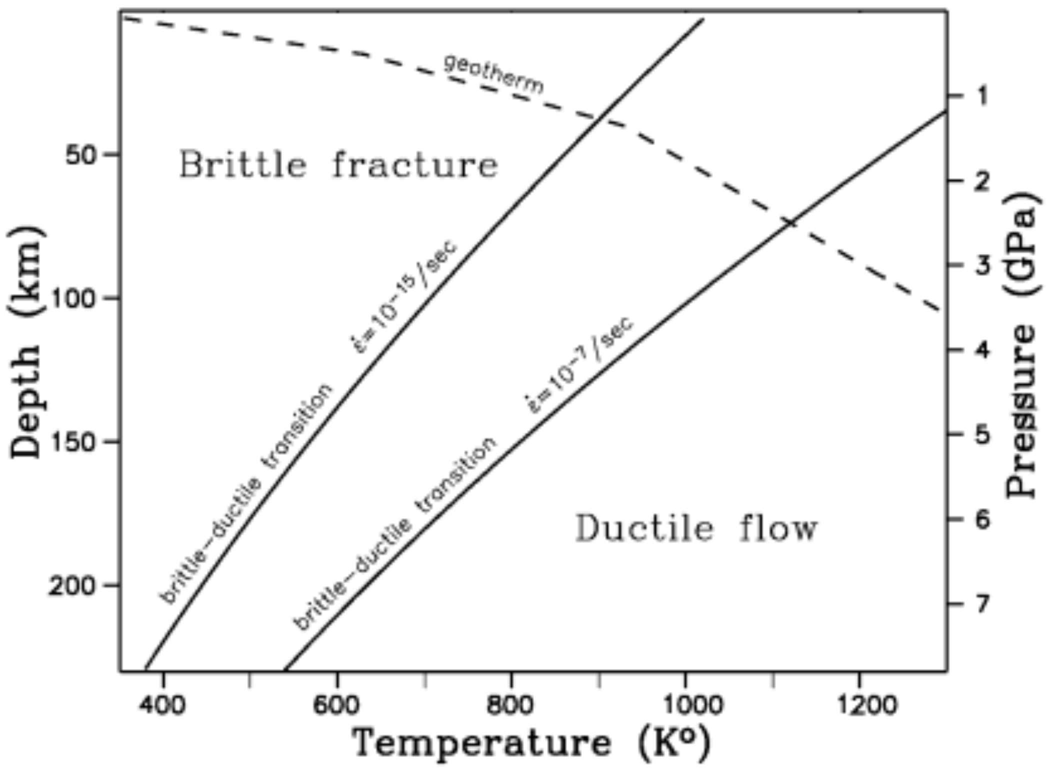
Mechanism is not well constrained



Occur at temperatures and pressures above the point where ordinary fractures ought to occur.

Frohlich (2006)

Intermediate Depth Earthquakes

Deep and Intermediate Depth Earthquakes

Depth > 50 – 60 km

25% of global earthquake catalogs

Mechanism is not well constrained

Proposed Mechanisms

Dehydration embrittlement

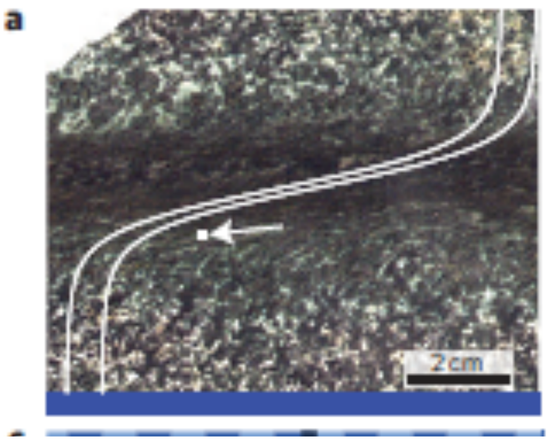
Thermal Shear runaway instability

Phase transformations

….

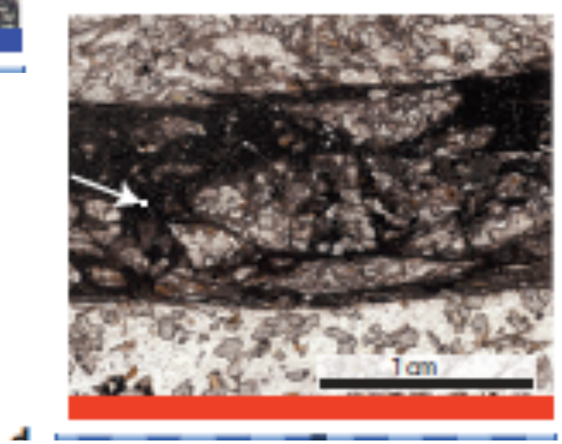
Runaway Instability

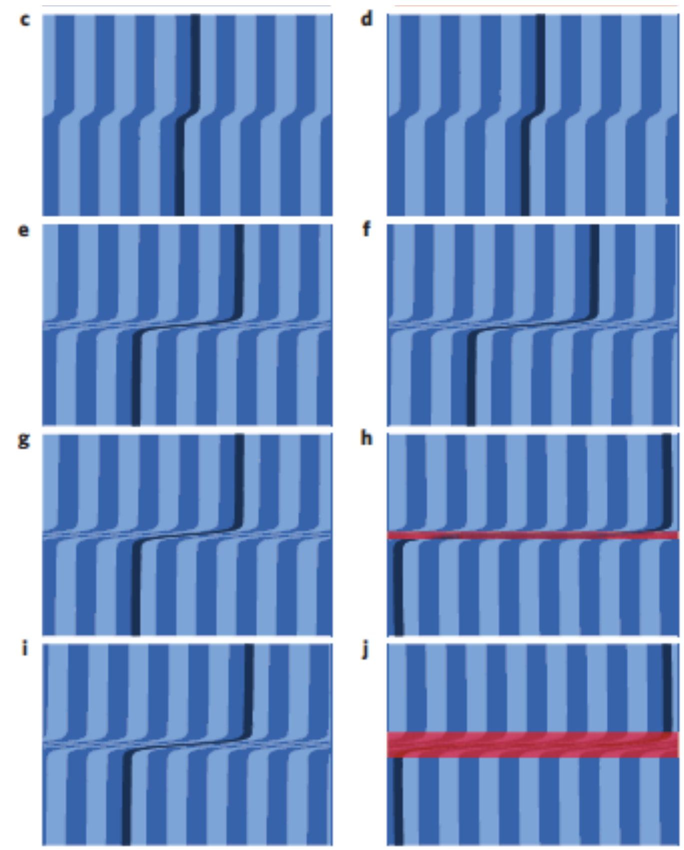
Deep and Intermediate Depth Earthquakes



Shear Zone

Pseudotachylite



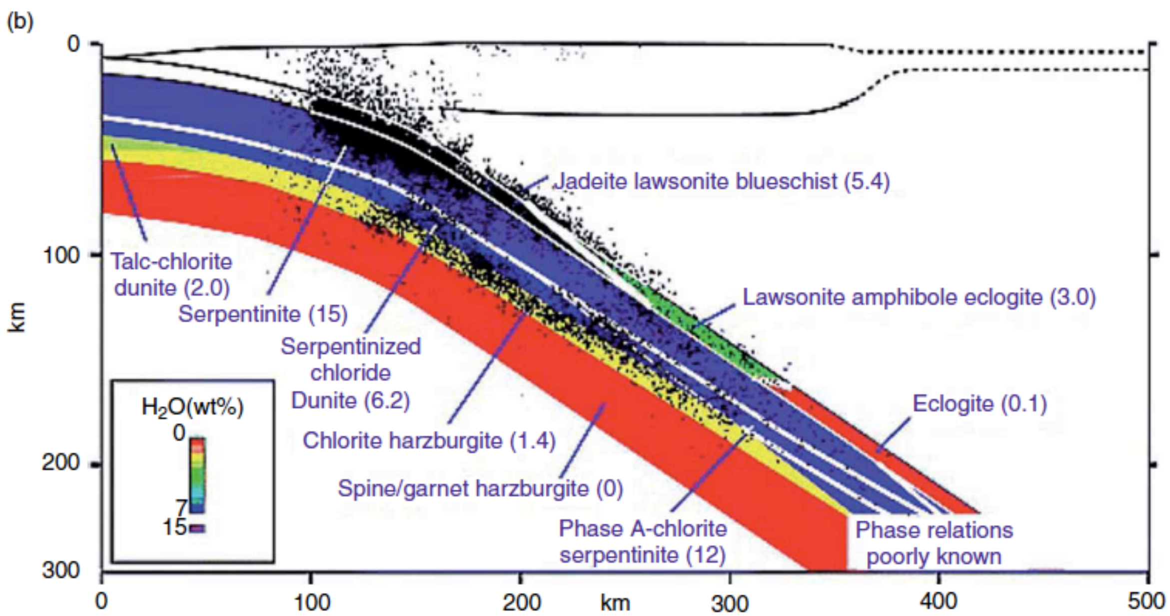


John et al., 2009
Nature Geoscience

"ductile deformation in shear zones leads to heating, thermal softening and weakening of rock"

Dehydration Embrittlement

"intermediate-depth double seismic zones consistent with dewatering of hydrous phases predicted from subduction zone thermal structures" (Houston, 2007)

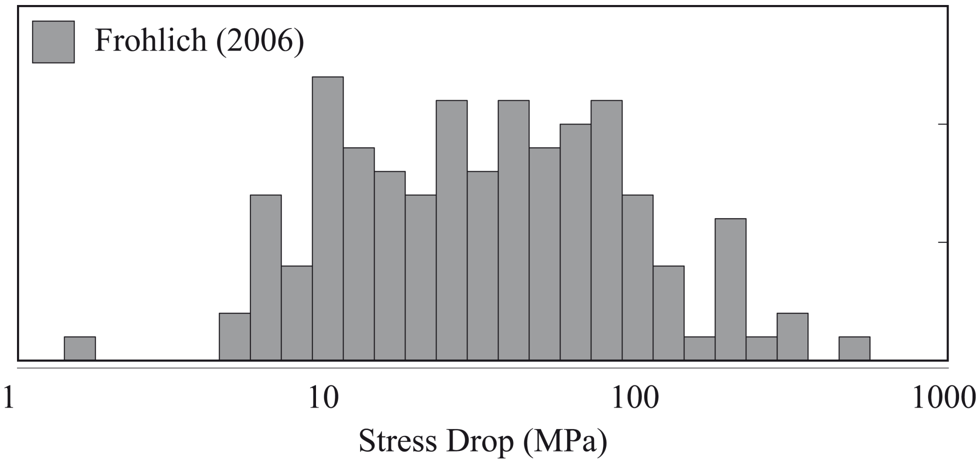


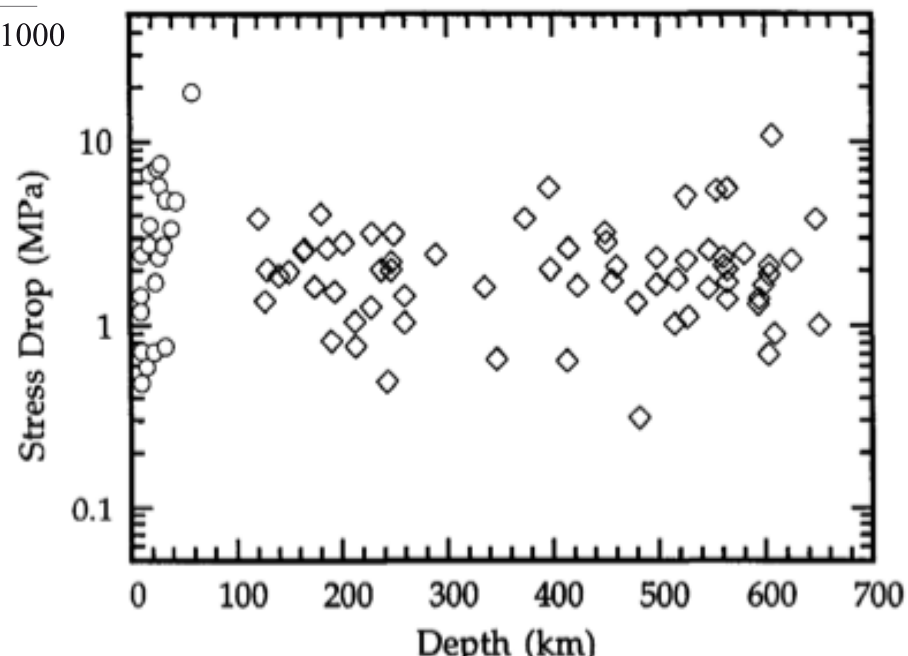
Hacker et al., 2003

"brittle failure assisted by high fluid pore pressures that counteract high normal stresses due to large pressures"

Deep Earthquakes

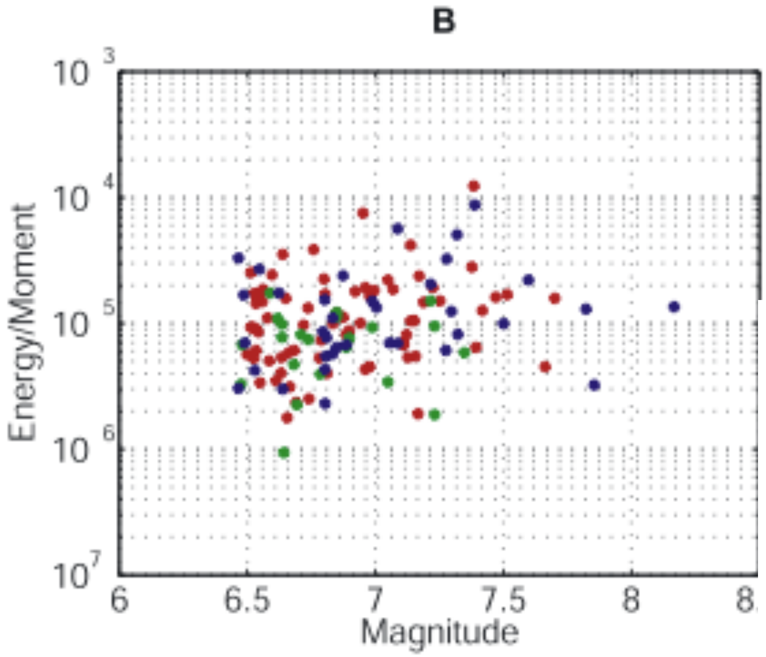
Source Parameters – Stress Drop

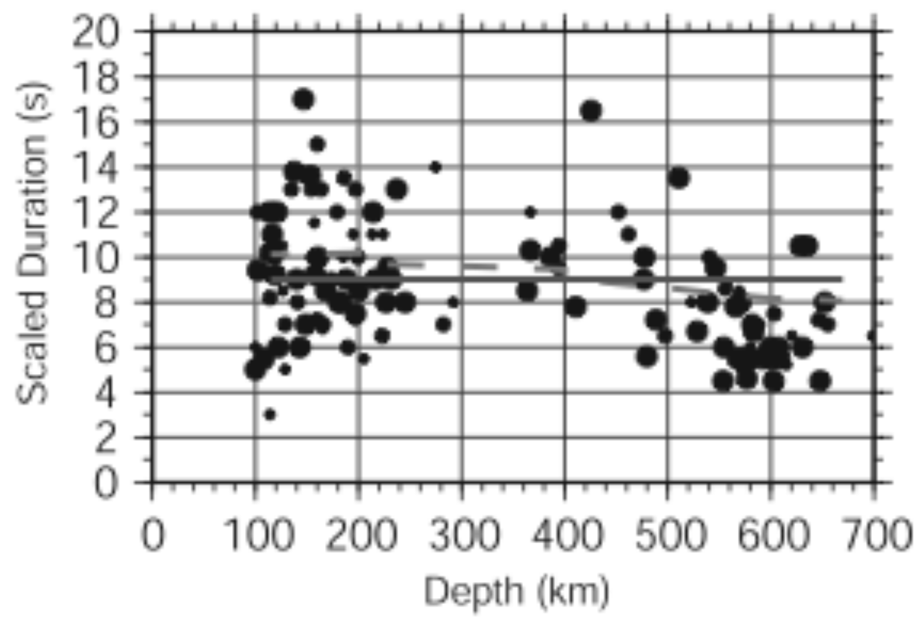




Houston (2007)

Source Parameters – Energy and Source Duration

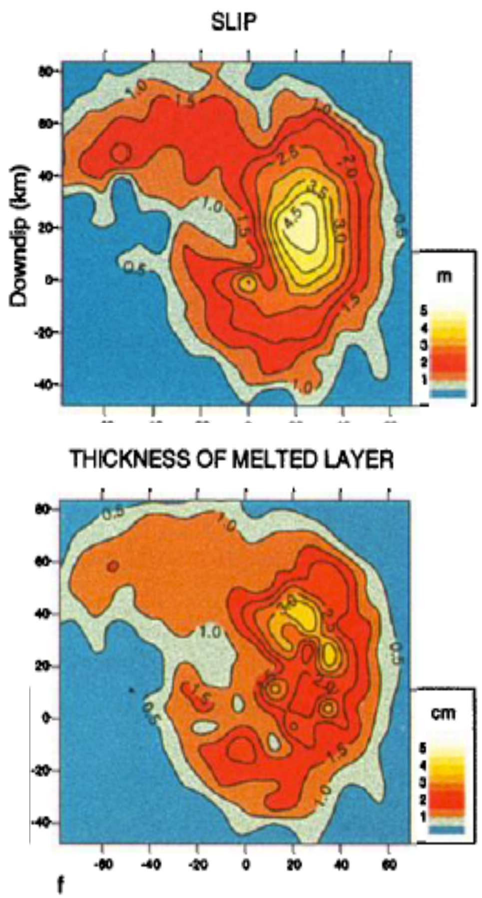




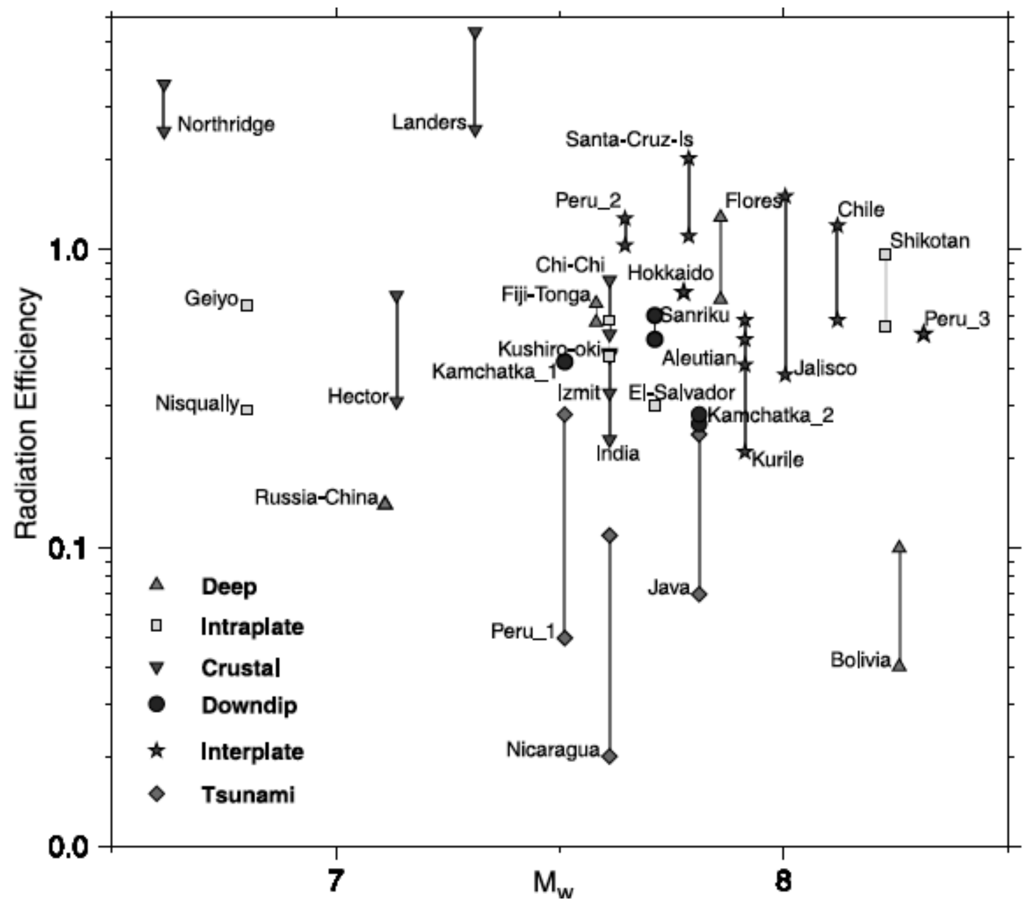
Tocheport et al. (2007)

Deep Earthquakes

Source Parameters – Radiation Efficiency



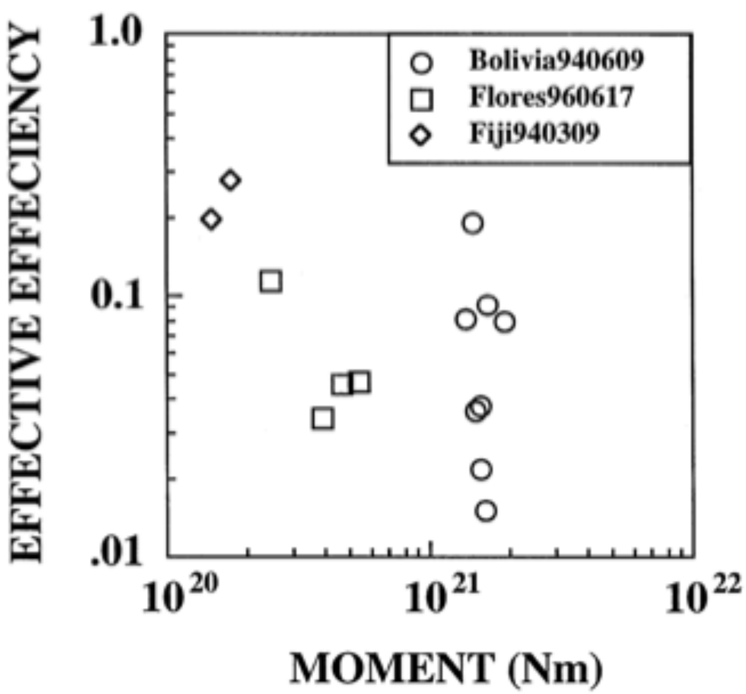
Venkataraman and Kanamori, 2004



Kanamori et al. (1998) and Bouchon et al (1999) show evidence of small seismic efficiency and frictional melting (Bolivian earthquake).

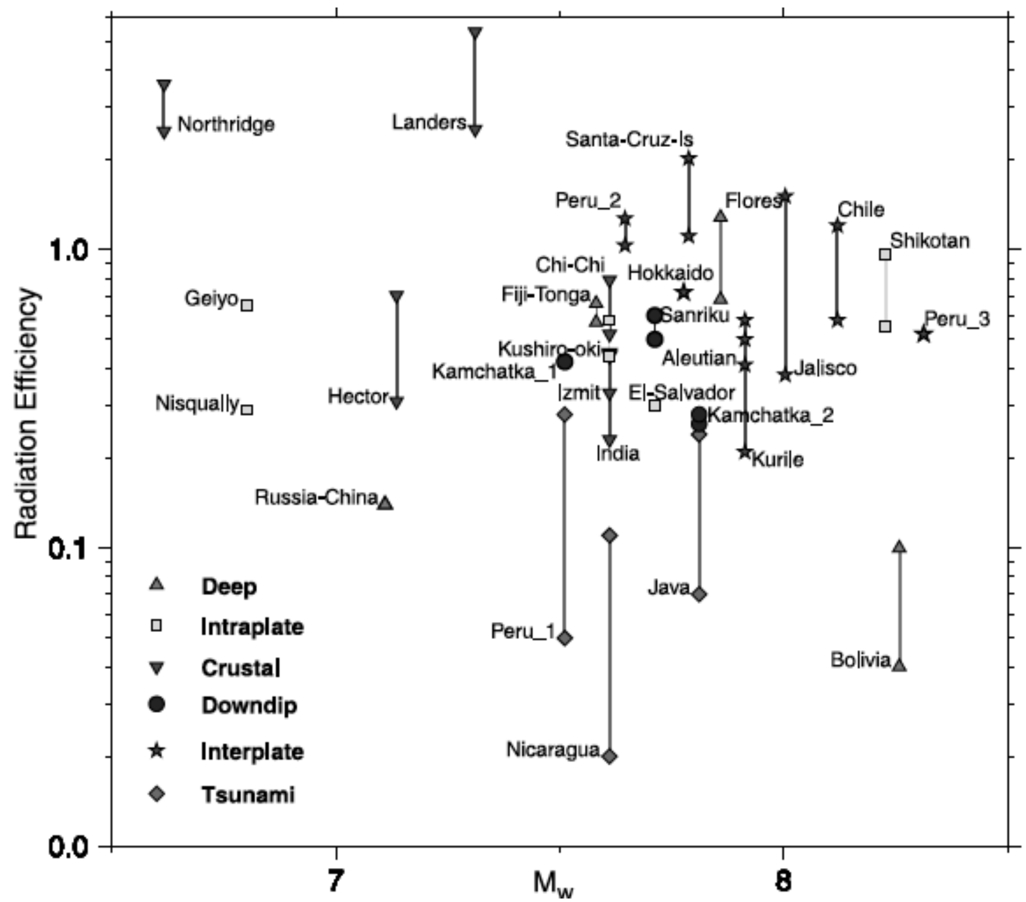
Deep Earthquakes

Source Parameters – Radiation Efficiency



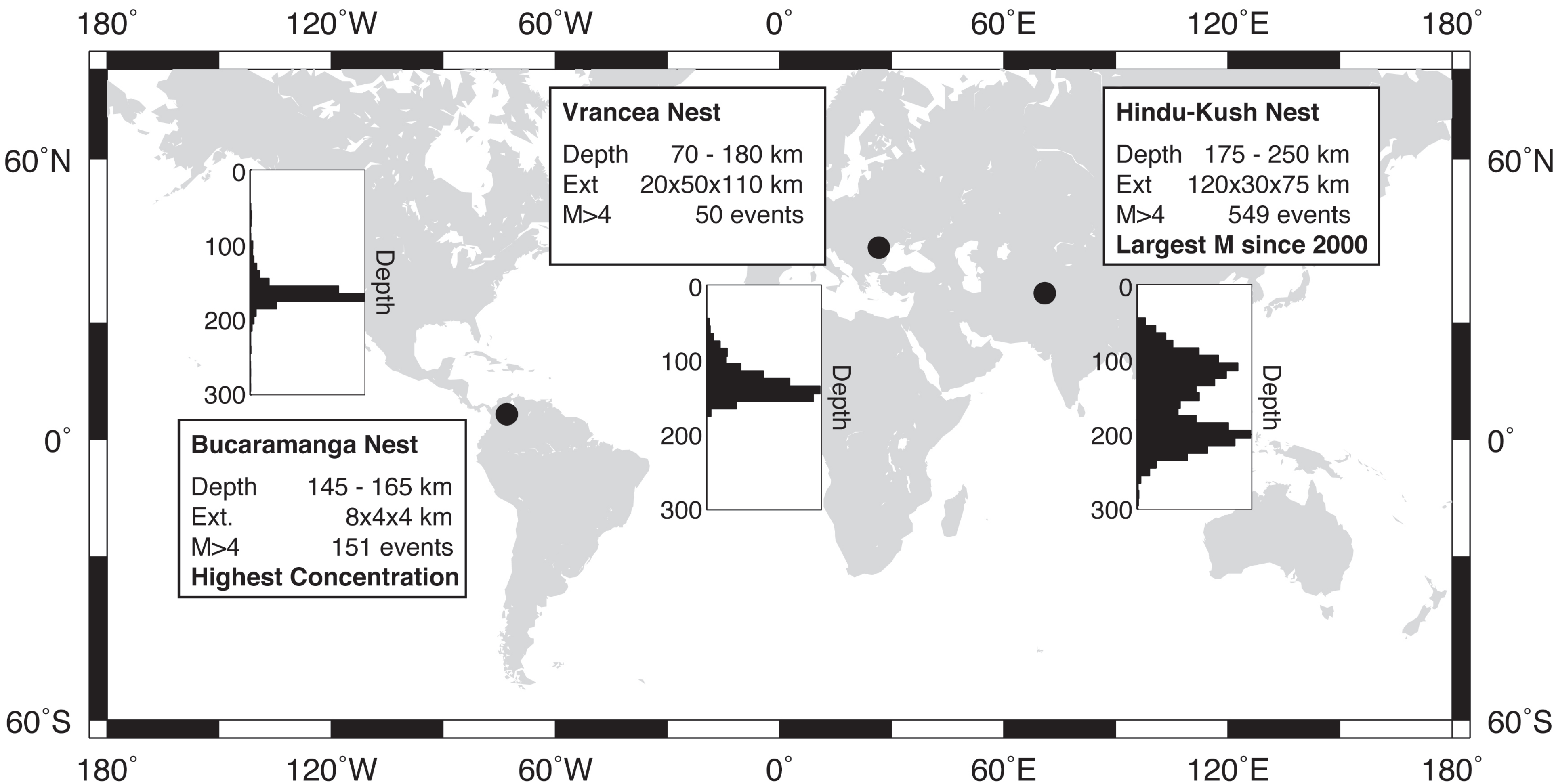
Winslow and Ruff, 1999

Venkataraman and Kanamori, 2004



Kanamori et al. (1998) and Bouchon et al (1999) show evidence of small seismic efficiency and frictional melting (Bolivian earthquake).

Intermediate Depth Earthquakes



Earthquake Nests

Hindu-Kush, Vrancea, Bucaramanga

The Bucaramanga Nest

Clear isolation of nest

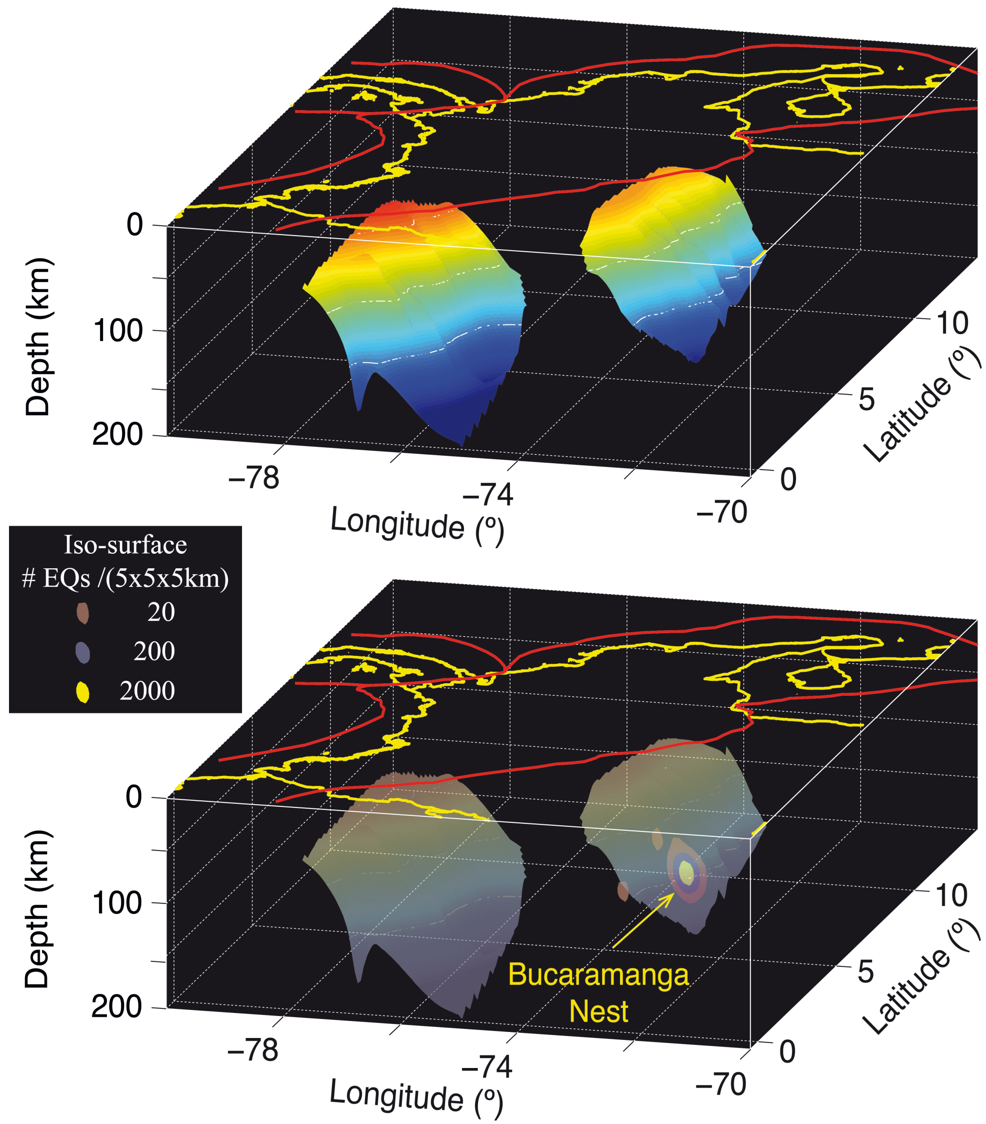
More than 2.000 earthquakes on a 5x5x5 km volume.

Bucaramanga Nest

Depths 145 – 165 km

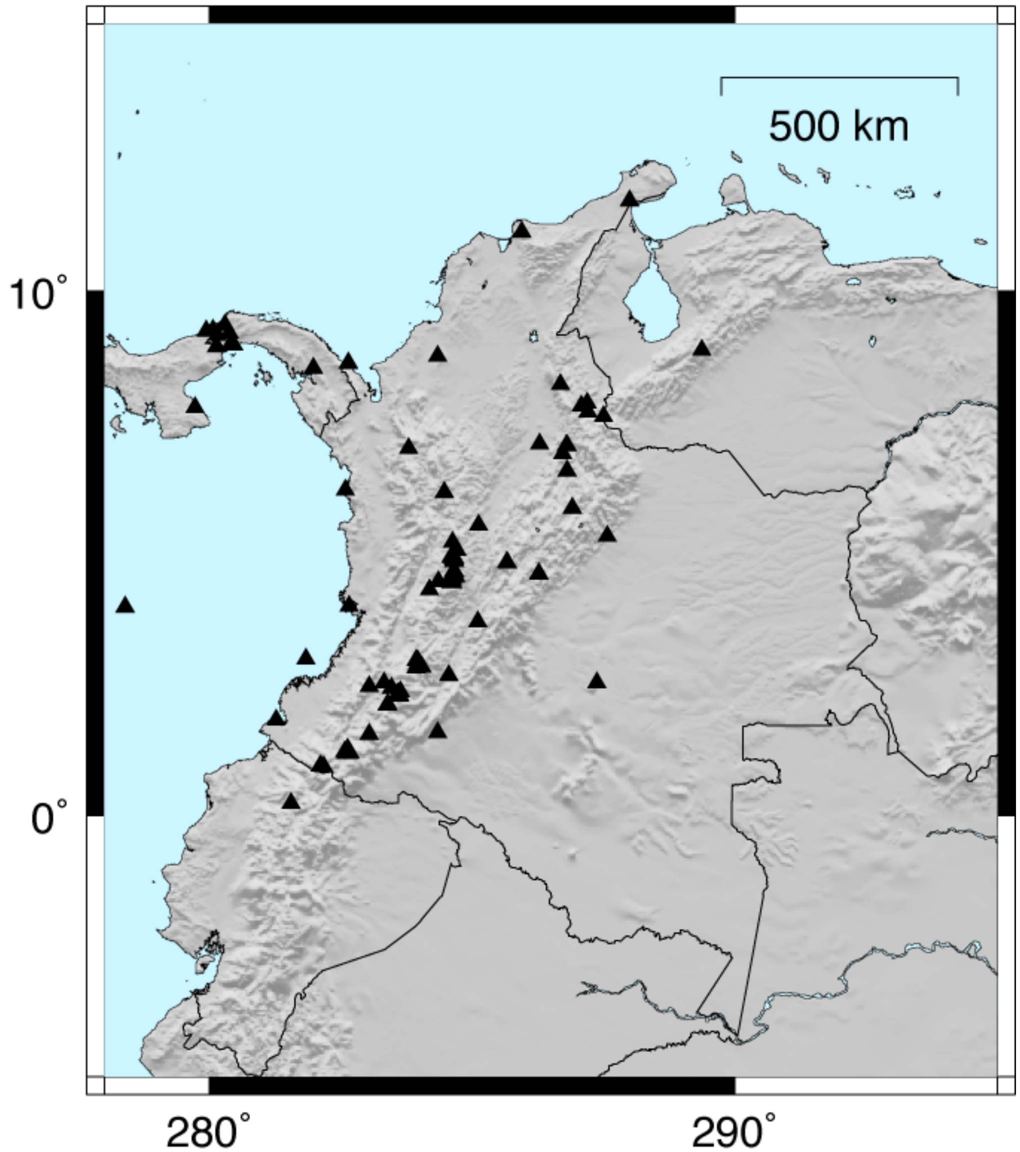
Caribbean Plate?

Most concentrated nest



Prieto et al, 2012

The Bucaramanga Nest – a Natural Laboratory



World's greatest concentration of intermediate-depth earthquakes.

Colombian network (RSNC)

15 B-nest earthquakes per day

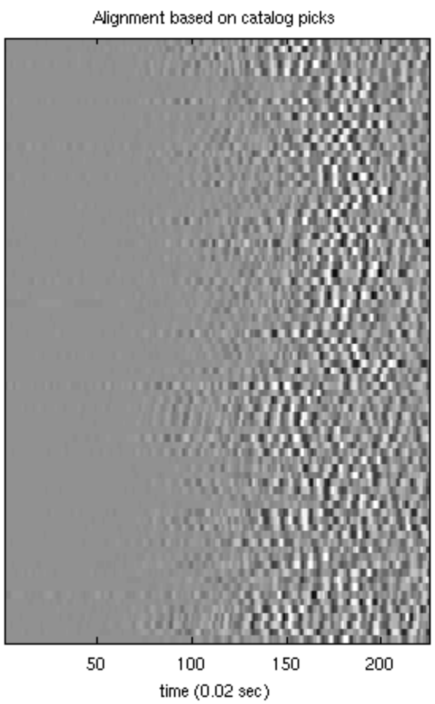
1 M_L 4.5 or greater per month.

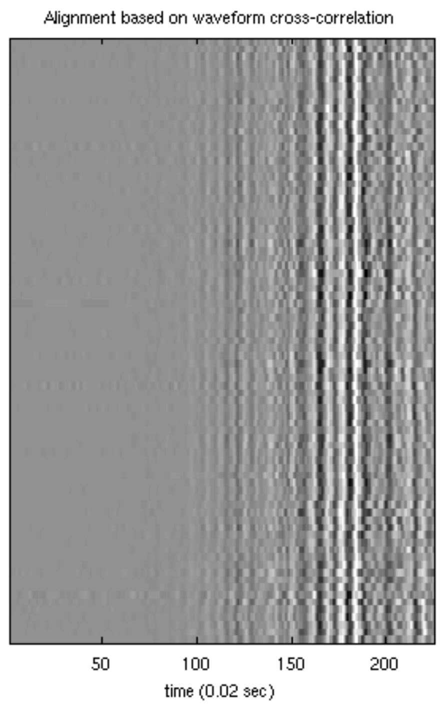
>60.000 B-Nest EQ (1993-2011)

Broadband and short period

Earthquake Source Physics

Earthquake Locations





Earthquake Relocations:

Double-Difference Algorithm
CC relative times

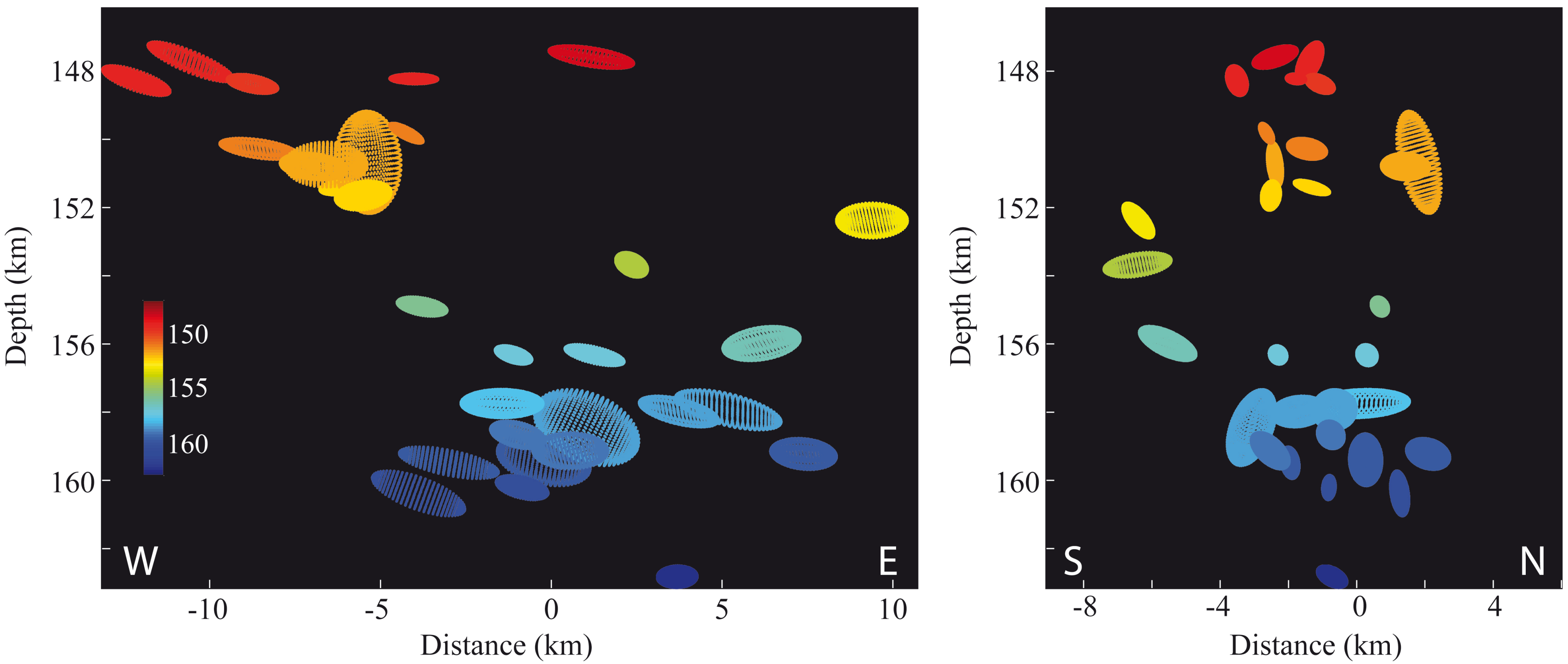
Total of 10-15 stations

Size of Nest radius from Catalog: ~40 km.

Schneider suggests a volume of 11 km^3

Earthquake Locations

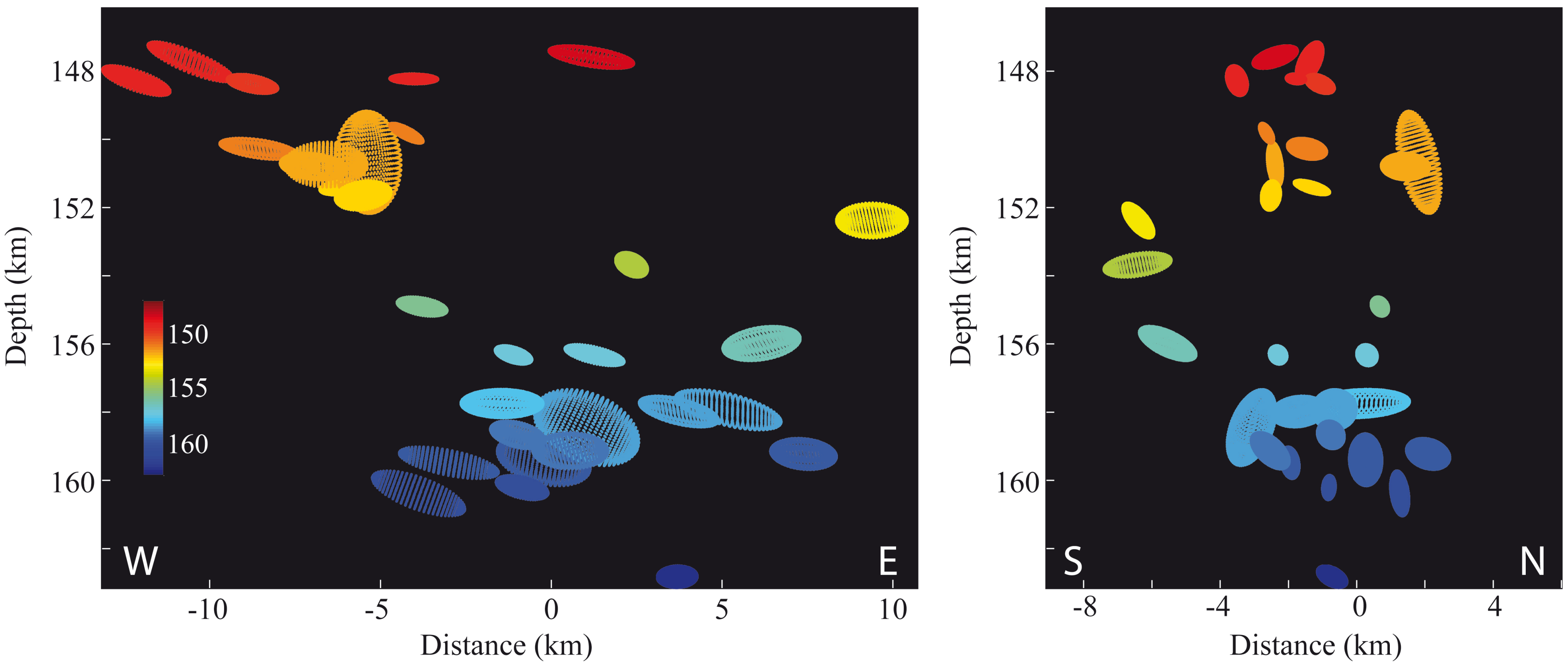
Relocated Bucaramanga Nest EQ



Relocated seismicity of M>4.0 earthquakes

Earthquake Locations

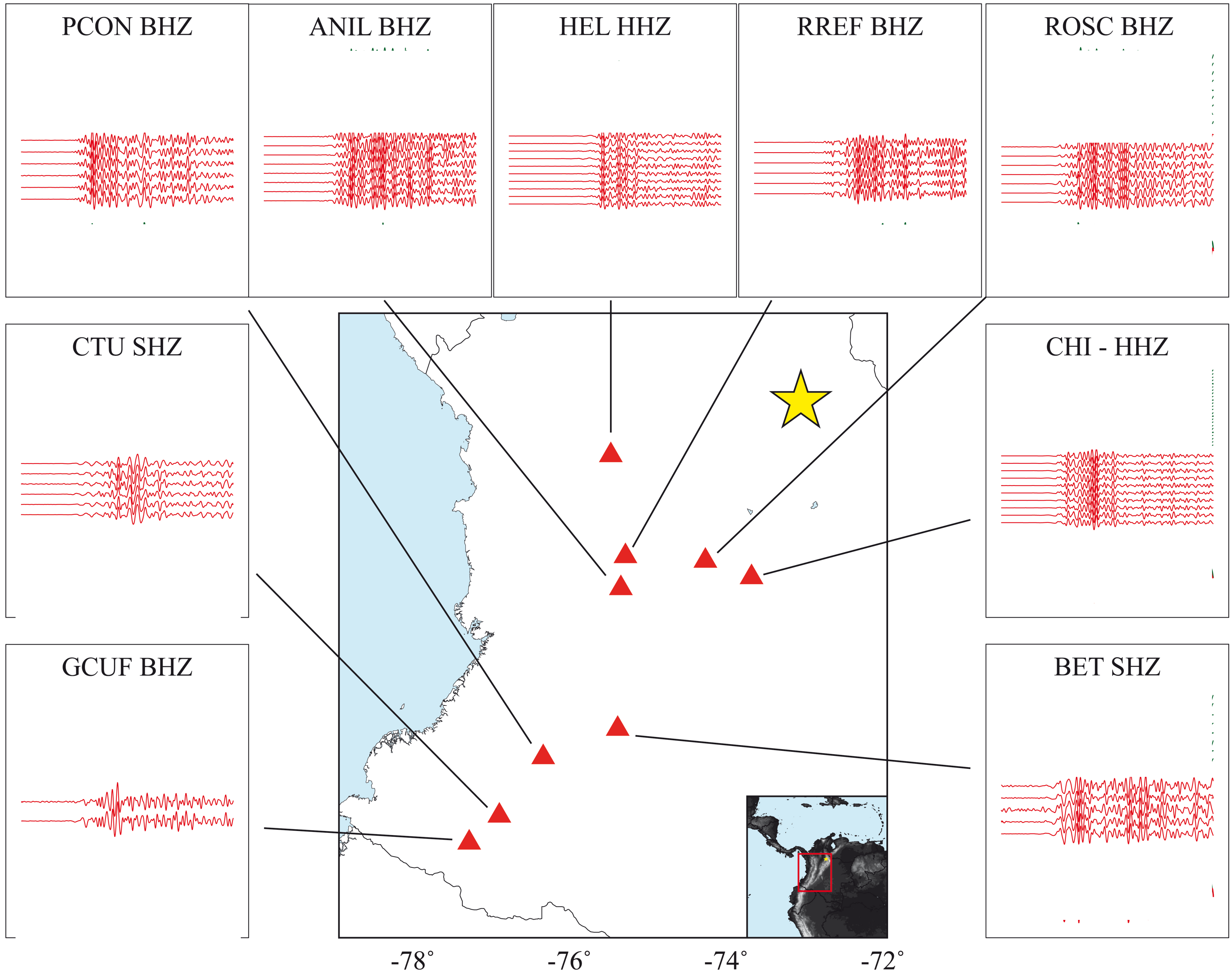
Relocated Bucaramanga Nest EQ

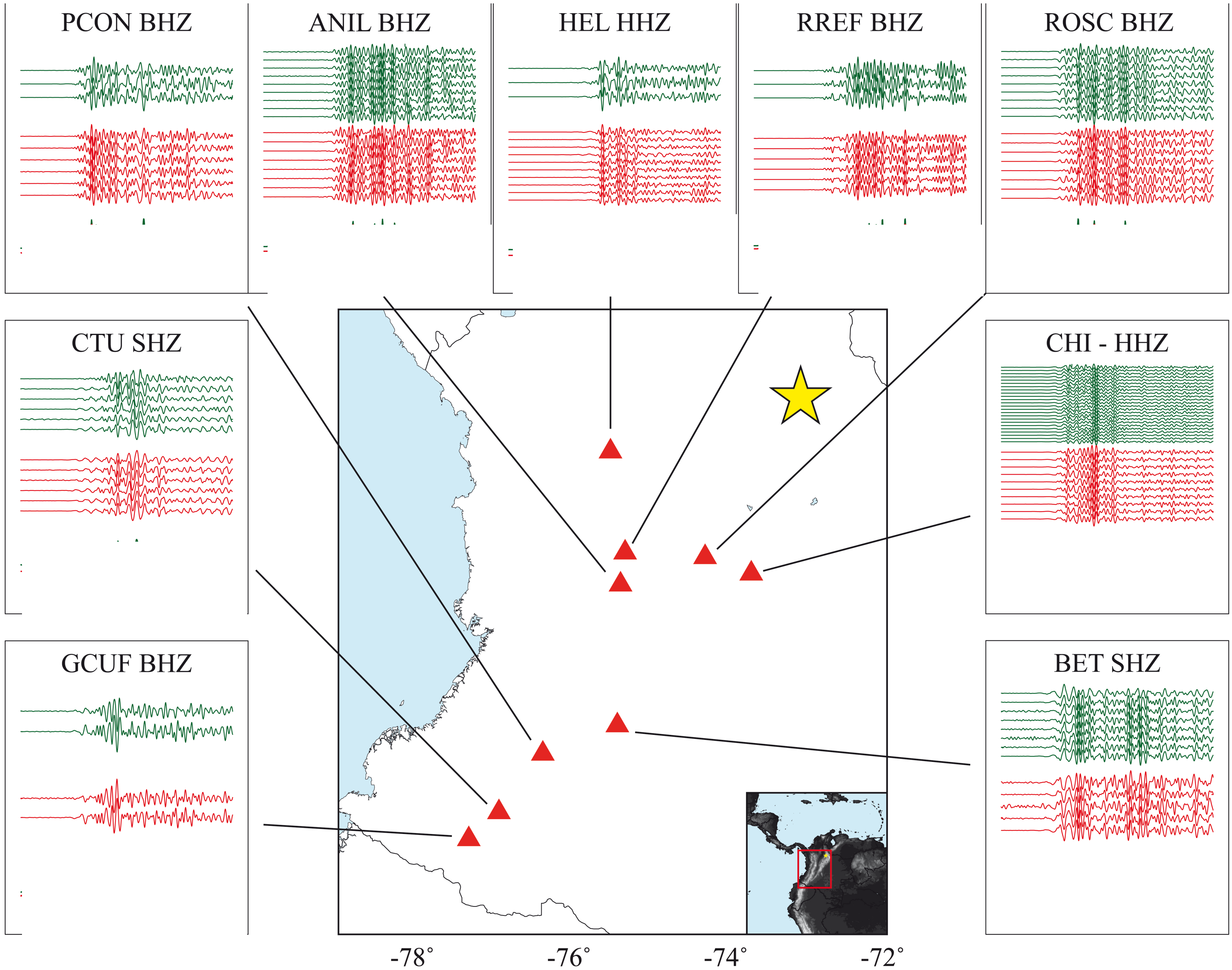


**BN relocated earthquakes show linear structures.
Ruptures along sub-horizontal faults? Repeating?**

Repeating Earthquakes?

Define Repeats:
CC > 0.9
At least 5 stations
Waveform similarity for 15 seconds after P-wave


PCON BHZ
ANIL BHZ
HEL HHZ
RREF BHZ
ROSC BHZ
CTU SHZ
CHI - HHZ
GCUF BHZ
BET SHZ
-78°
-76°
-74°
-72°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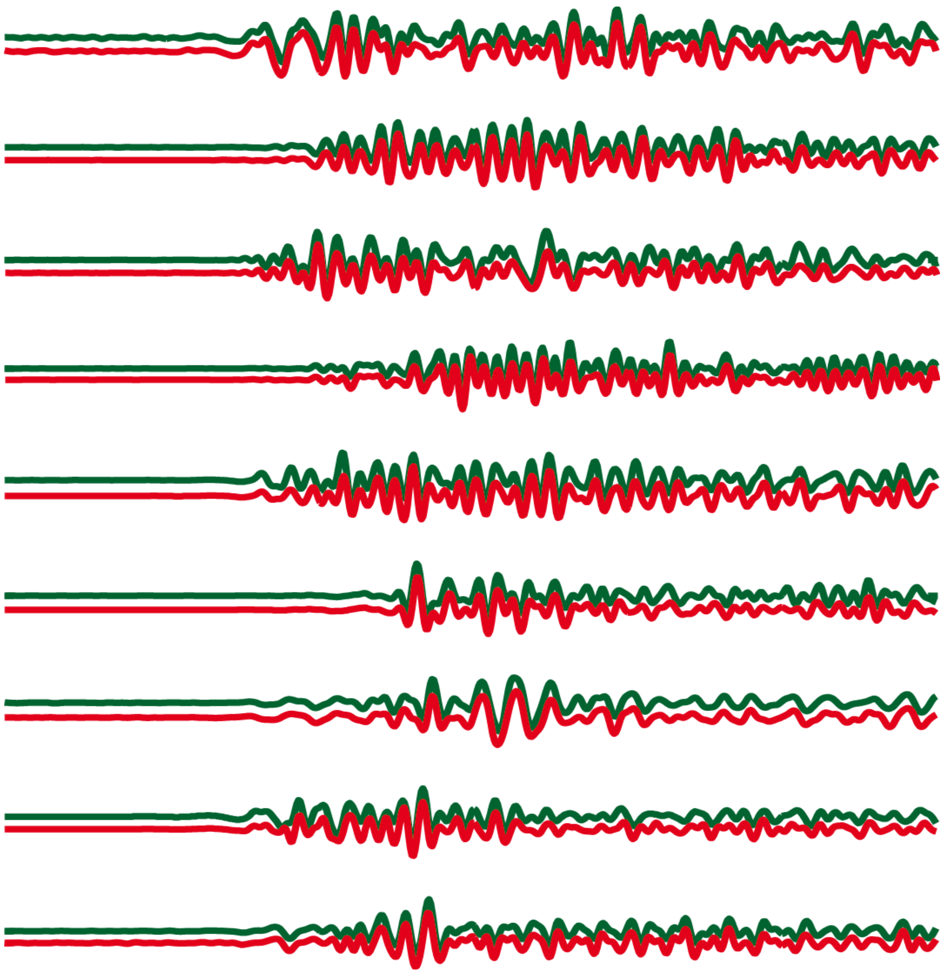
BET SHZ
-78°
-76°
-74°
-72°

Repeating Earthquakes?

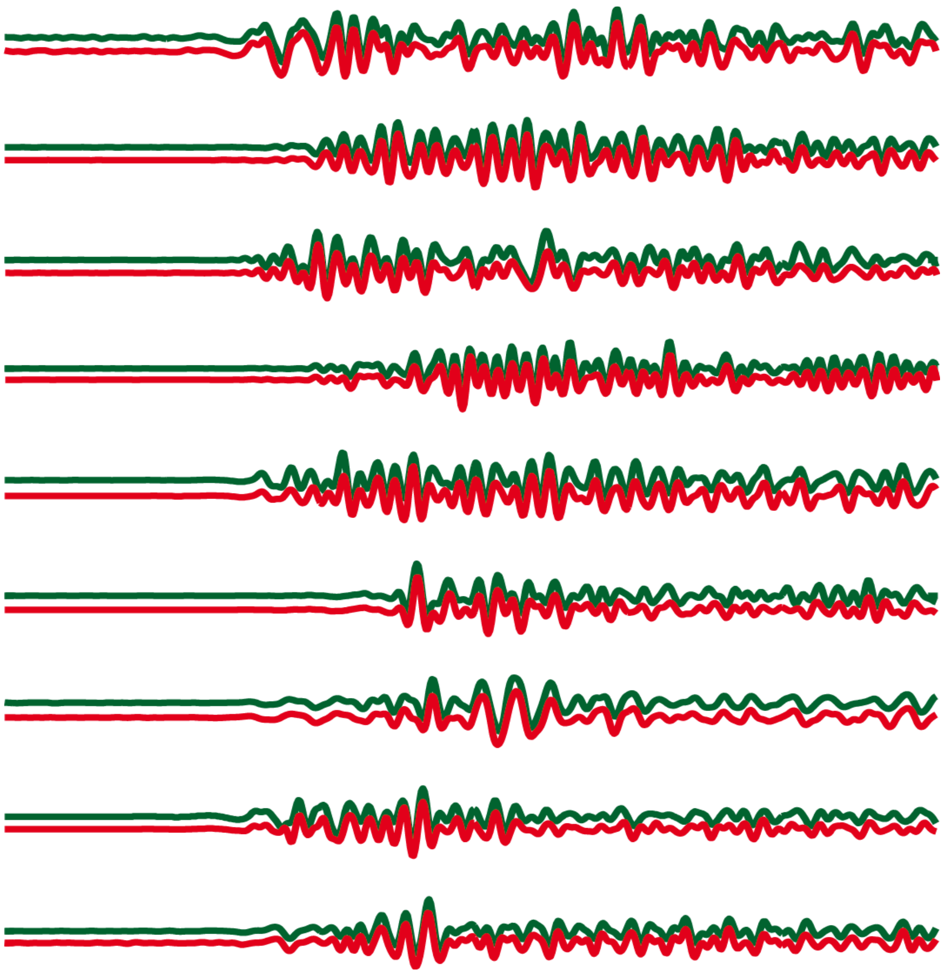
15 seconds shown.
Green signal flipped.



Large number of repeating and reversed polarity earthquakes

Repeating Earthquakes?

15 seconds shown.
Green signal flipped.



Dehydration embrittlement
Don't expect repeating Eqs

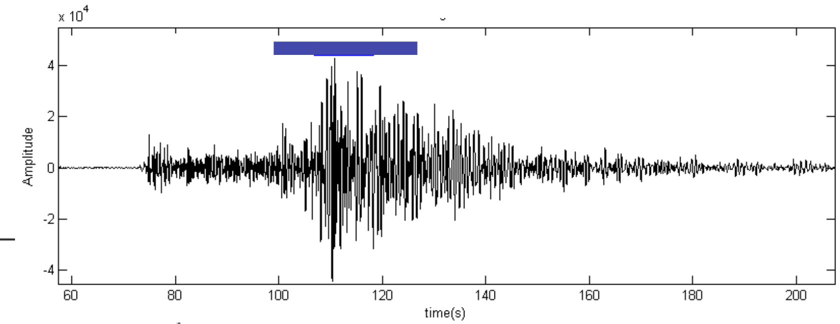
Shear Instability
May explain repeats.

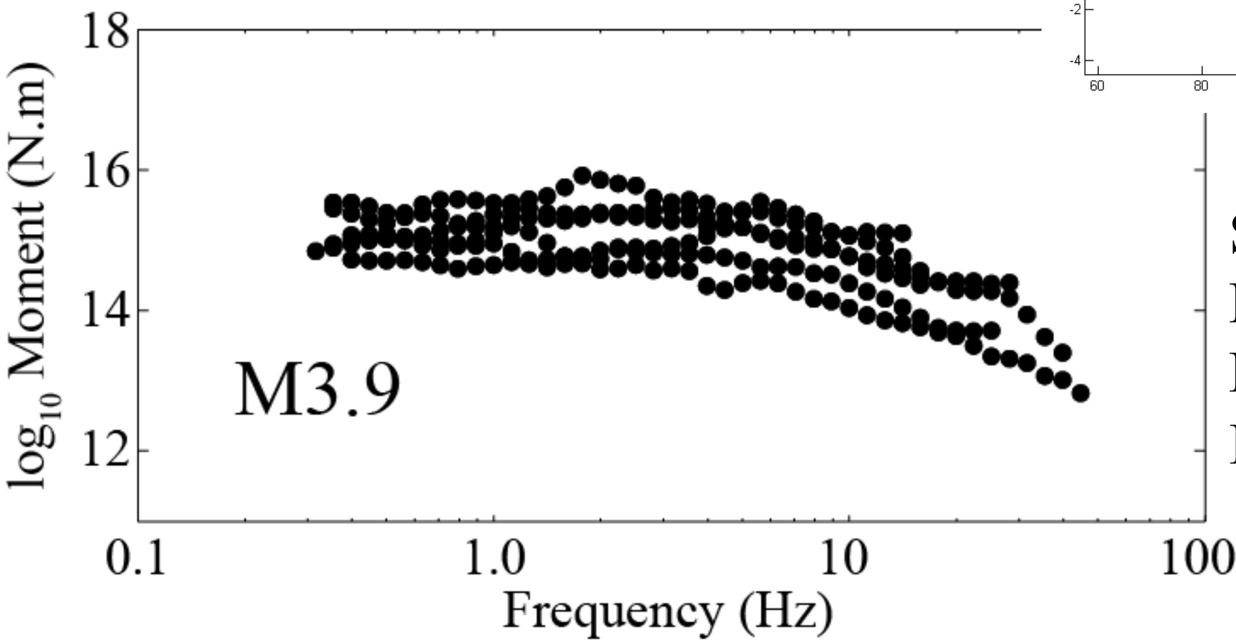
How can we explain "anti-repeats"?

Earthquake Source Physics

Energy Budget and Rupture size

Estimating Source Parameters





S - source

R – Near receiver

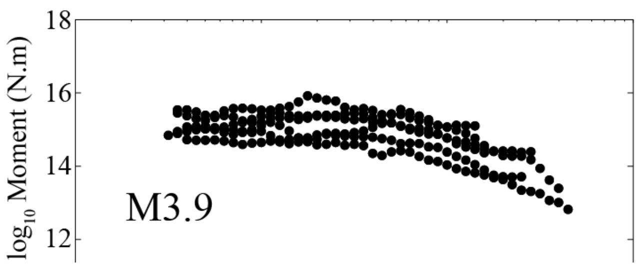
P – Propagation (Q, G)

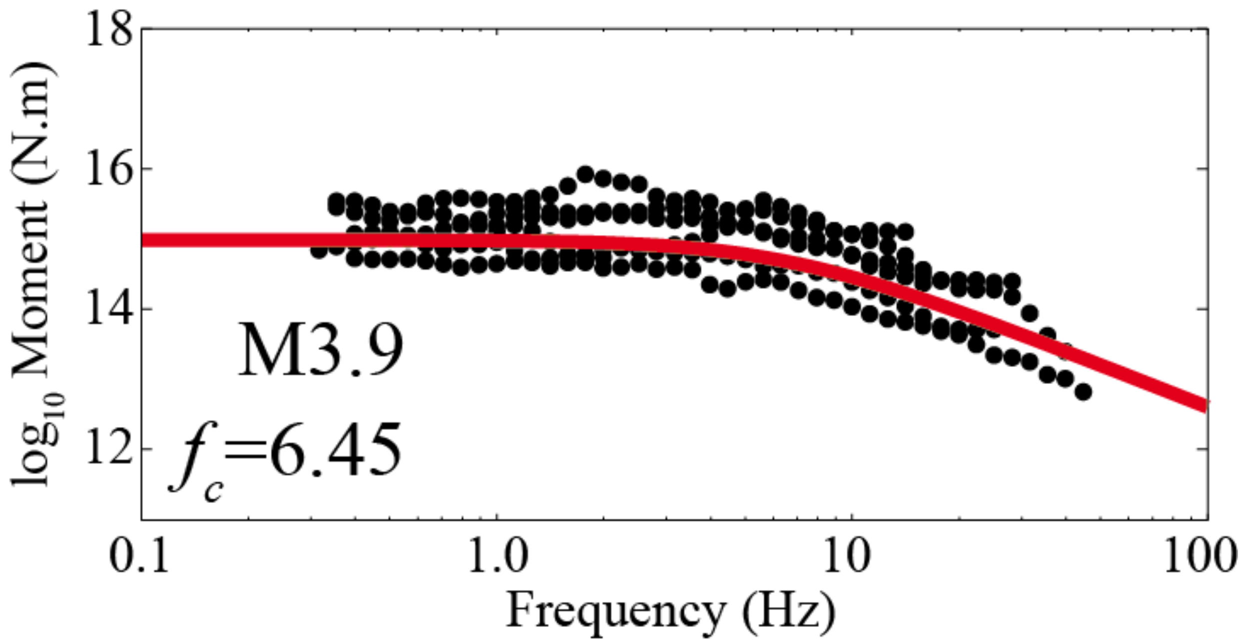
I – Instrument Response

$$U(f) = S(f) \cdot R(f) \cdot P(f) \cdot I(f)$$

1. **Estimate spectra *U(f)* from time series for each station**
2. **Remove propagation and instrument effects, isolate *S(f)***

Estimating Source Parameters

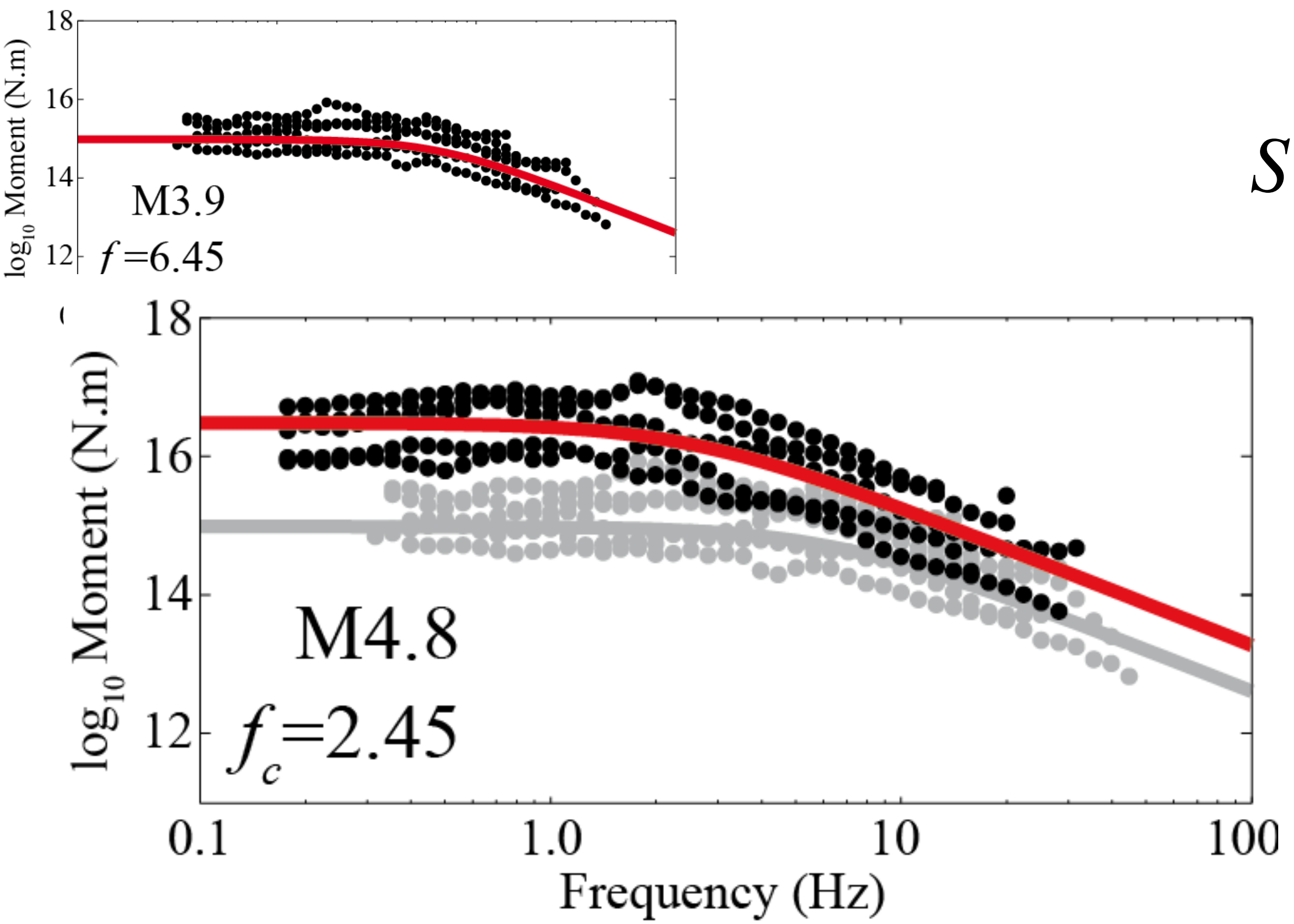




$$S(f) = \frac{M_0}{1 + \left(f / f_c \right)^2}$$

3. Fit earthquake source model (Brune-type)

Estimating Source Parameters

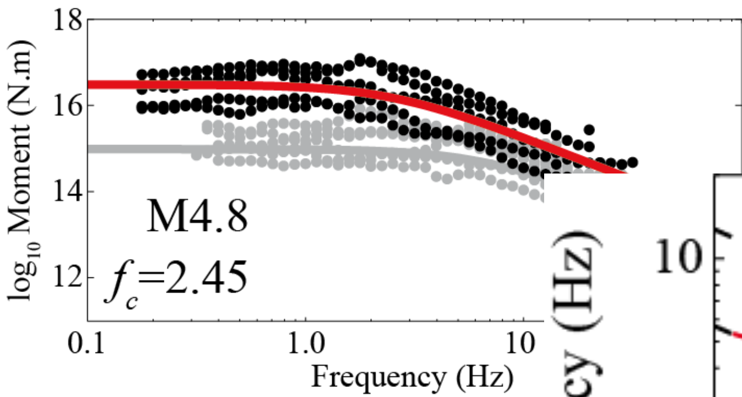


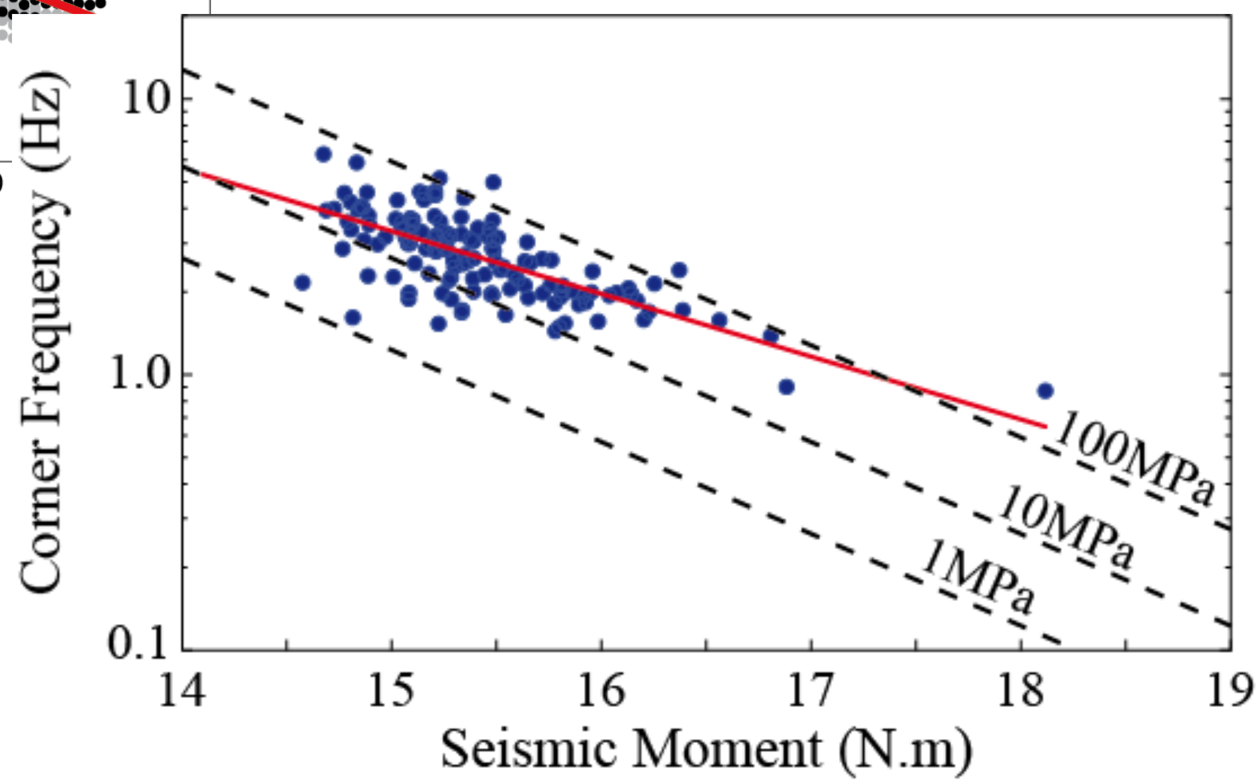
$$S(f) = \frac{M_0}{1 + \left(f / f_c \right)^2}$$

3. Fit earthquake source model (Brune-type)

4. Repeat for all events, all stations (150 earthquakes M>3.8).

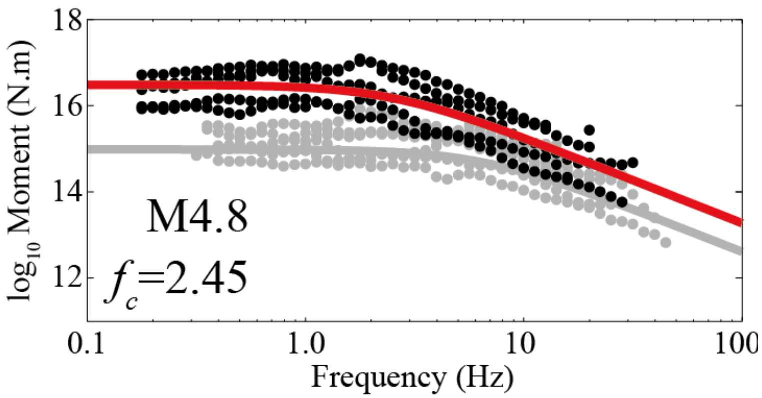
Corner frequencies and Source Radius

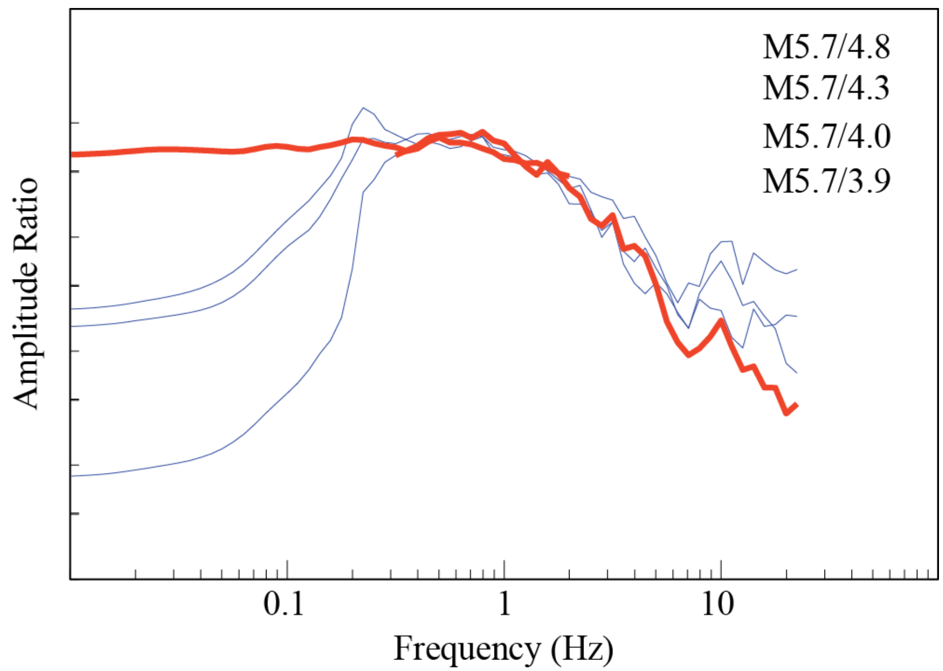




$$S(f) = \frac{M_0}{1 + \left(f \big/ f_c \right)^2}$$

Example Spectral Ratio M5.7





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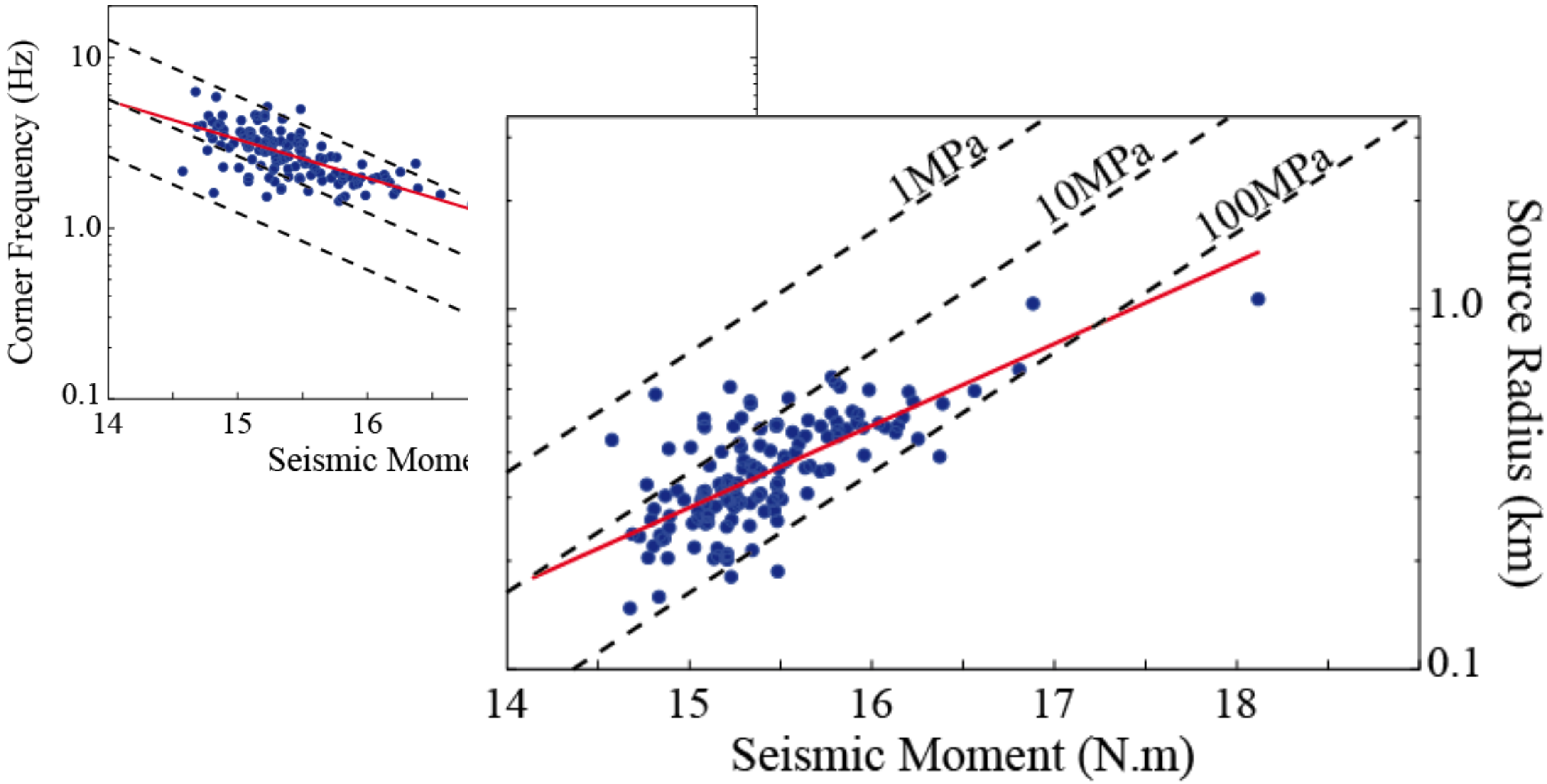
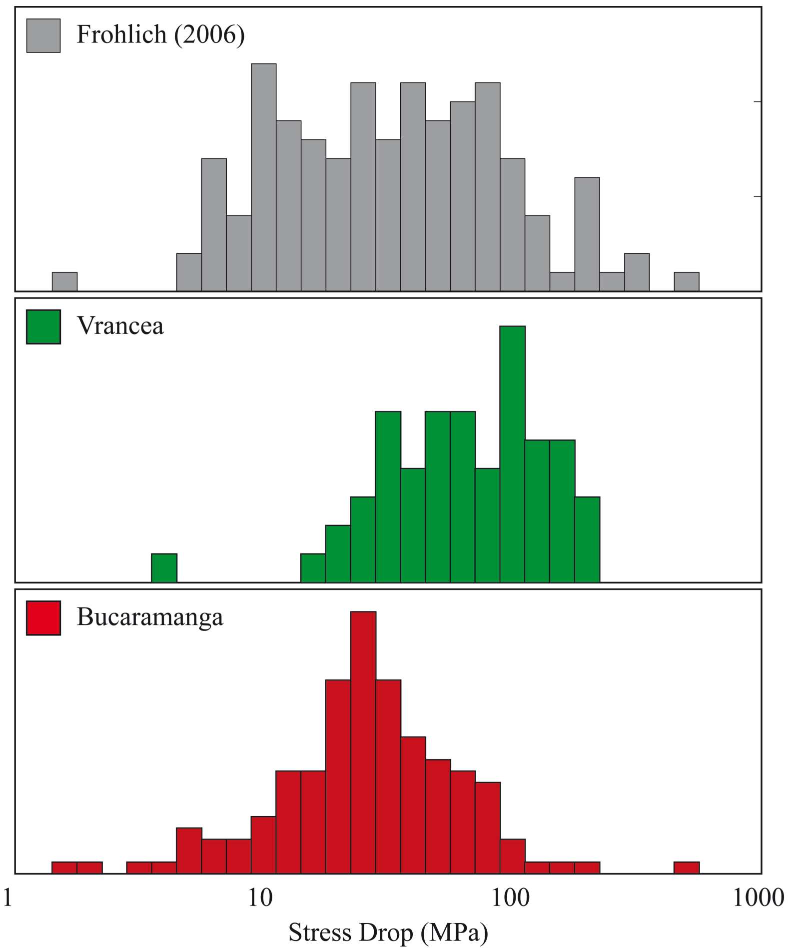
Corner frequencies and Source Radius

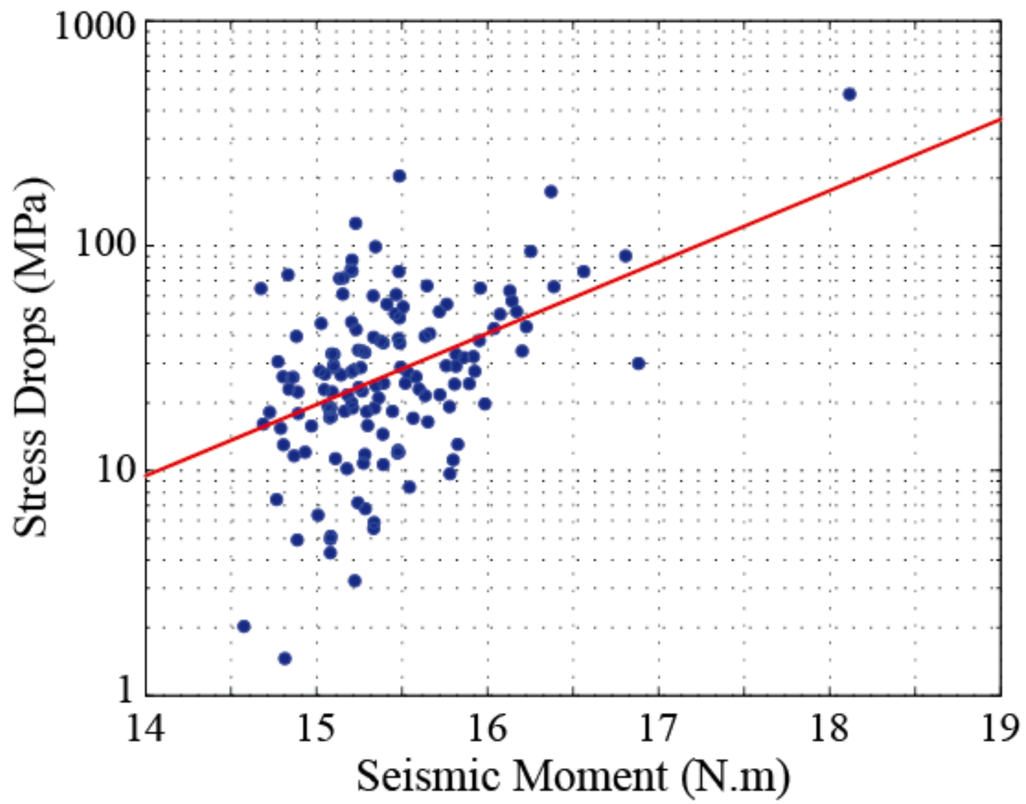


Small source area (1 km for a M5.7 earthquake)

Leads to very high Stress Drops

Stress Drops



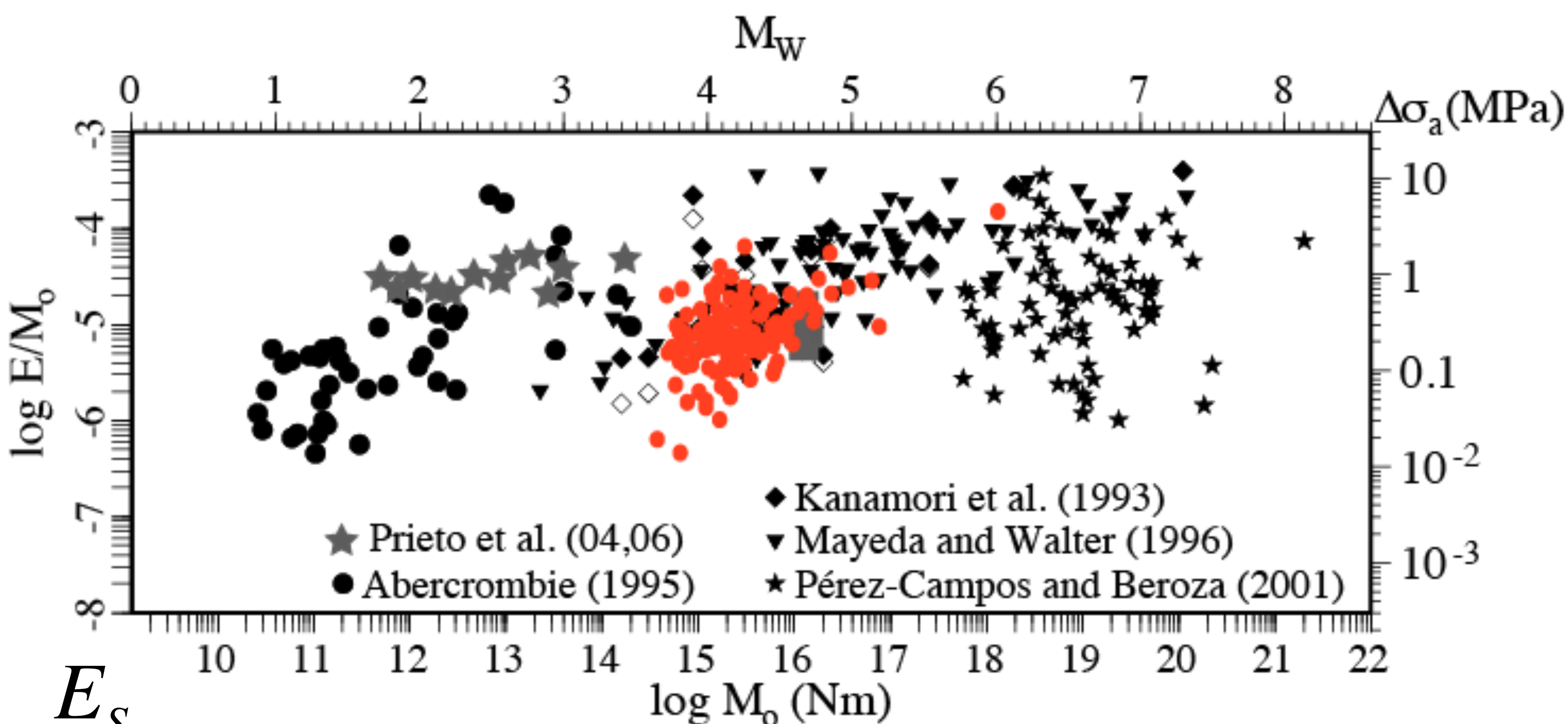


Very high Stress Drops

Large uncertainties due to f_c^3 and β^3 dependencies

Radiated Seismic Energy / Scaled Energy

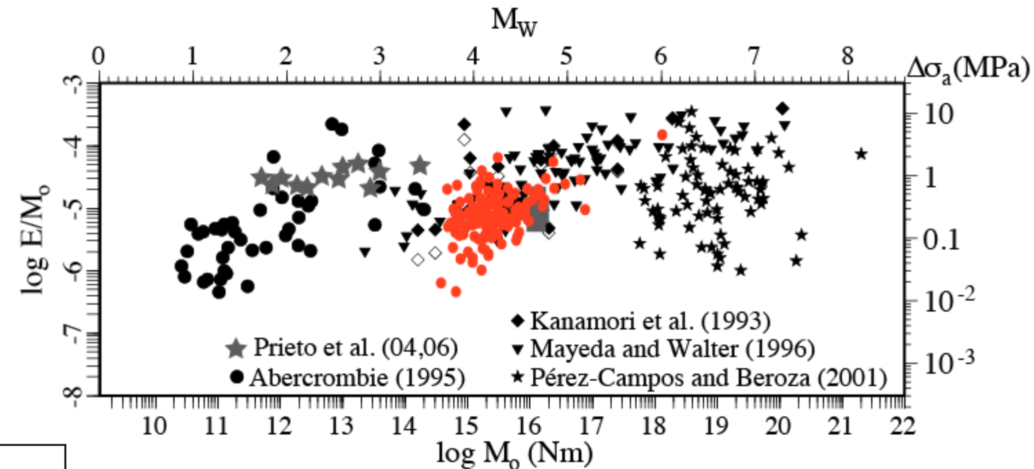
IDE AND BEROZA: DOES APPARENT STRESS VARY WITH EARTHQUAKE SIZE?

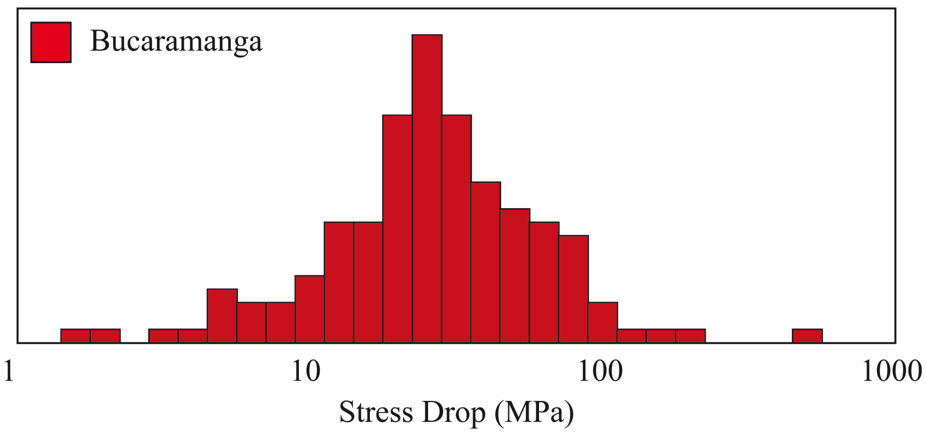


$$\sigma_a = \mu \frac{E_S}{M_0}$$

Scaled energies not anomalous, average below 1MPa.
Shows strong scaling.

Radiation Efficiency





$$\eta \propto \frac{2\sigma_a}{\Delta\sigma} \approx 0.045$$

Relatively large stress drops, small apparent stress.
Suggests very small seismic efficiency (~0.045)

Conclusions

Results favor:

Bucaramanga Nest shows linear trend in relocated earthquakes

Larger number of repeating & “anti-repeating” earthquakes observed

High stress drops, small seismic efficiencies.

Conclusions

Results favor:

Bucaramanga Nest shows linear trend in relocated earthquakes
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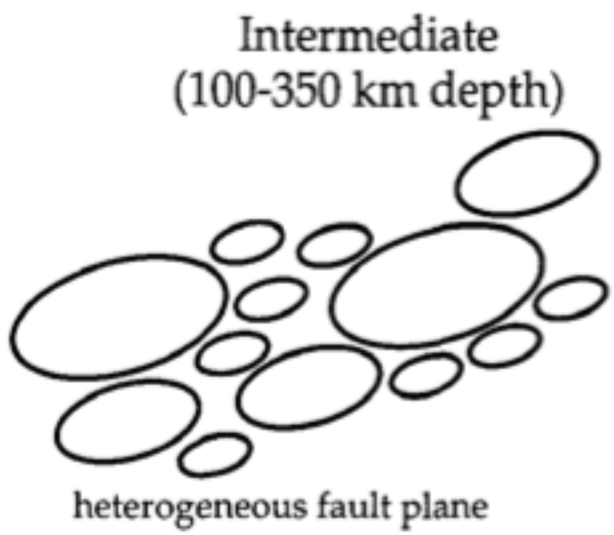
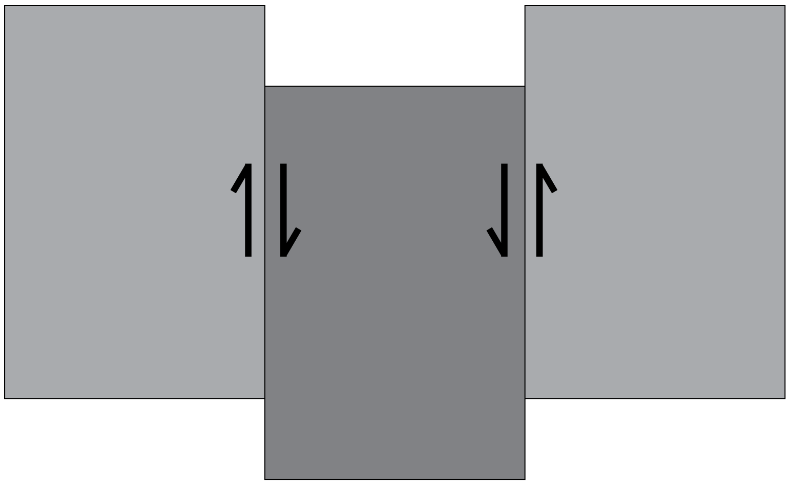
High stress drops, small seismic efficiencies.

What is the mechanism for repeating-reversed polarity earthquakes?



Houston and Green, 1999

Extruding block model



Conclusions

Results favor:

Bucaramanga Nest shows linear trend in relocated earthquakes
Larger number of repeating & "anti-repeating" earthquakes observed
High stress drops, small seismic efficiencies.

Dehydration embrittlement

No repeats expected.
Seismic efficiencies this small?
Linear trends and rupture along sub-horizontal faults?

Thermal Shear Runaway

Repeats possible, may indicate T dissipation slow.
Seismic efficiencies are expected to be small. Frictional melt?
Why is Pseudotachylite observed everywhere?

THANK YOU !