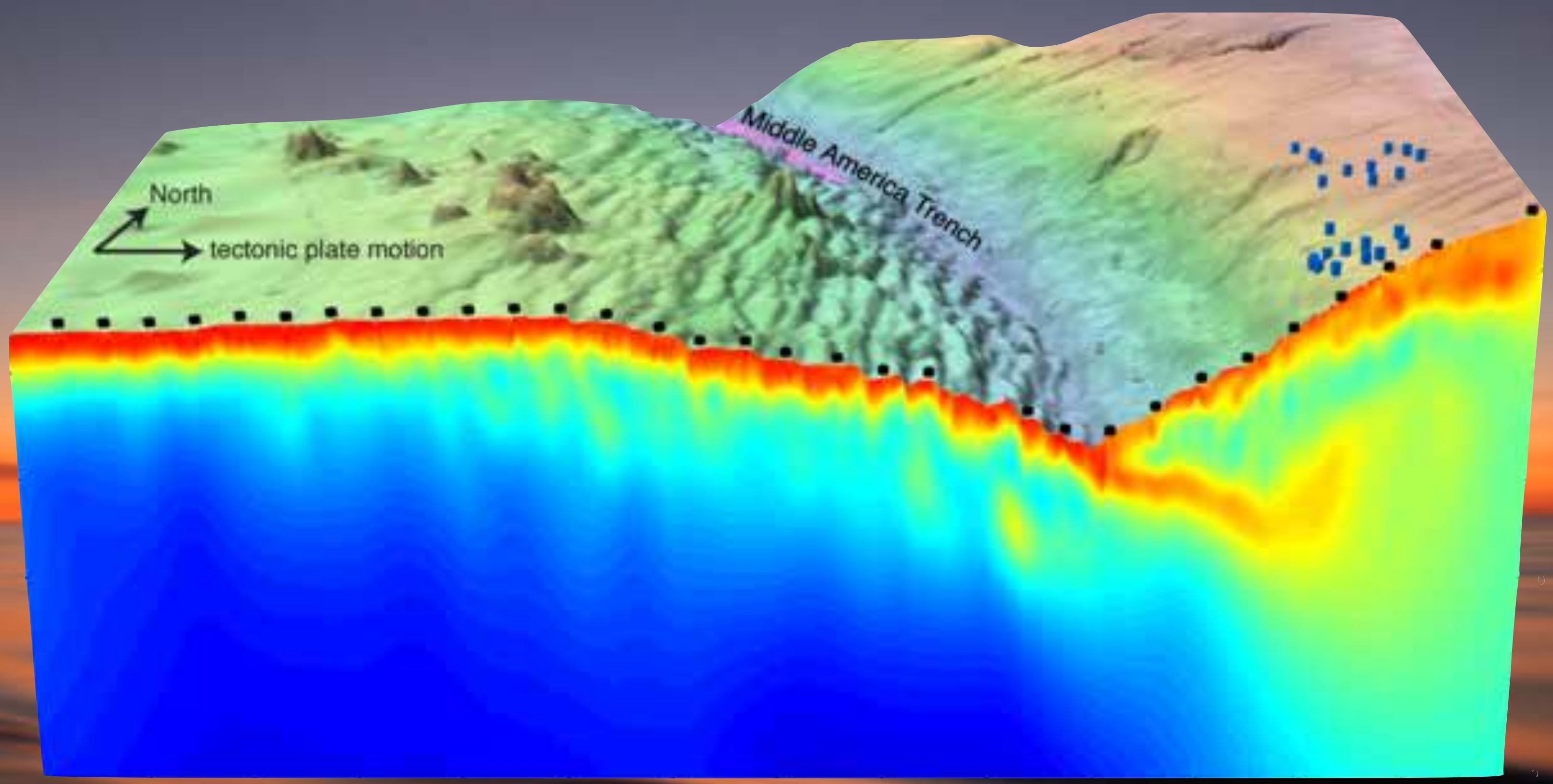
Controlled-source electromagnetic imaging of the Middle America Trench offshore Nicaragua



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NSF

Central America tectonic setting

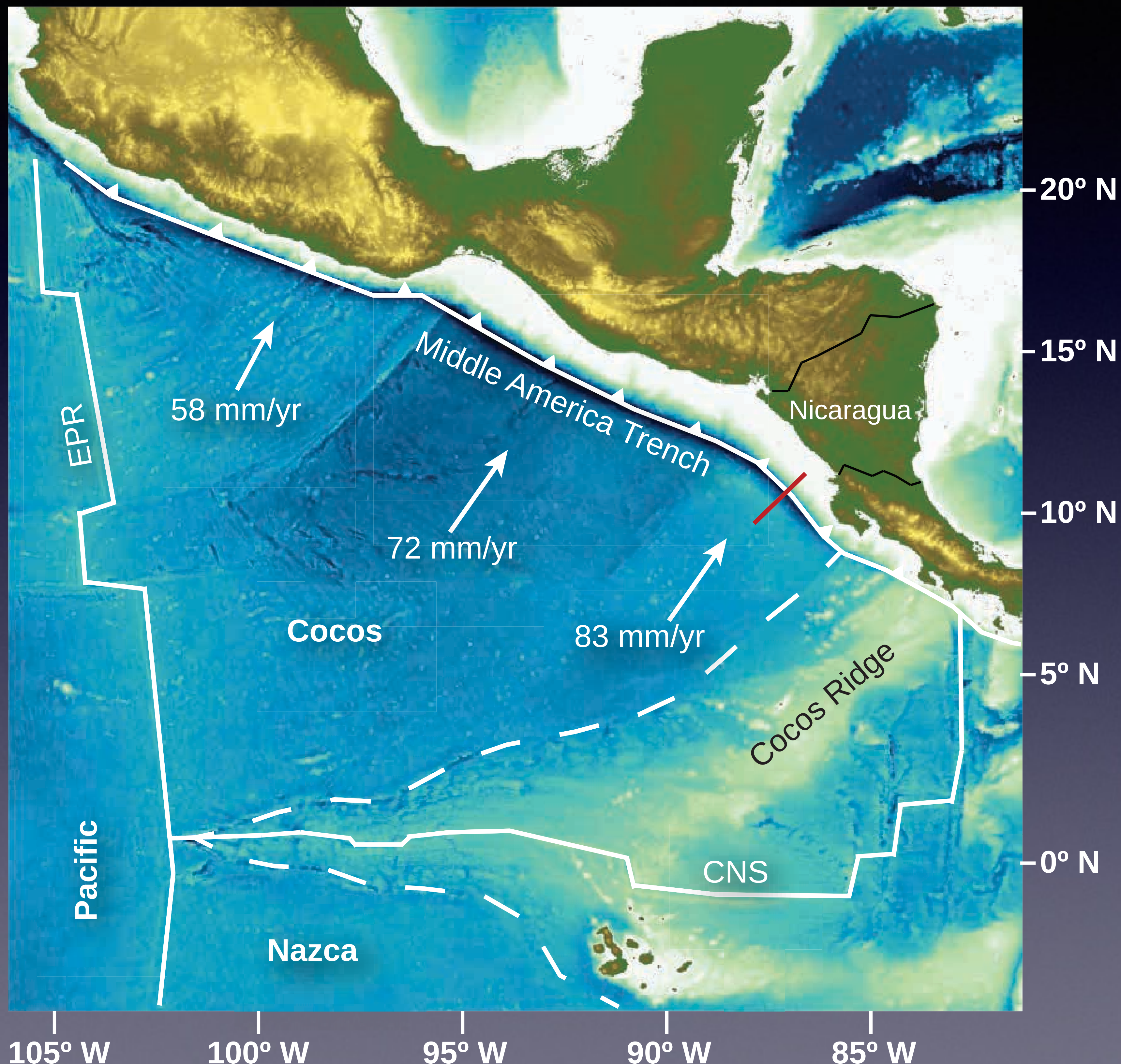
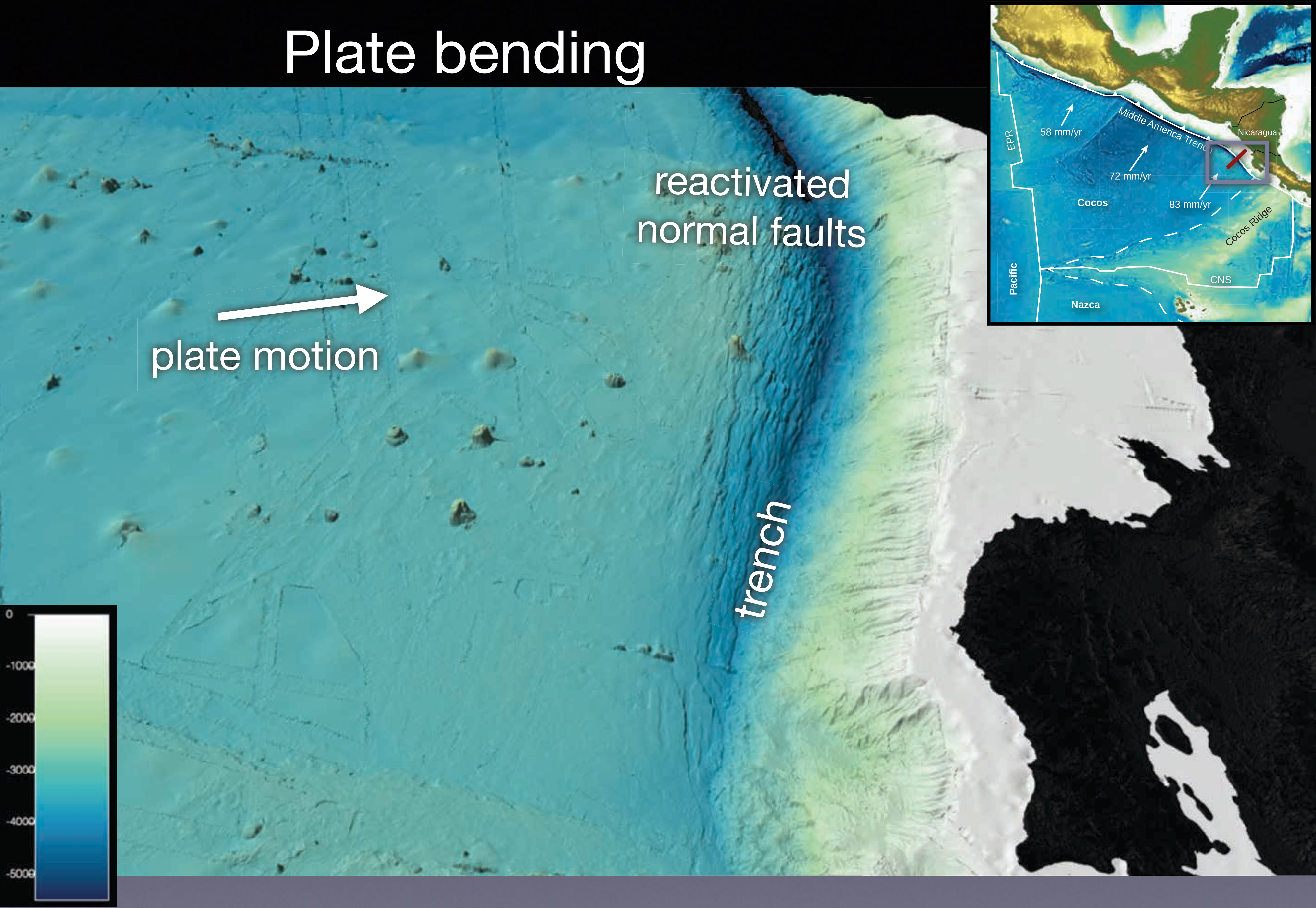
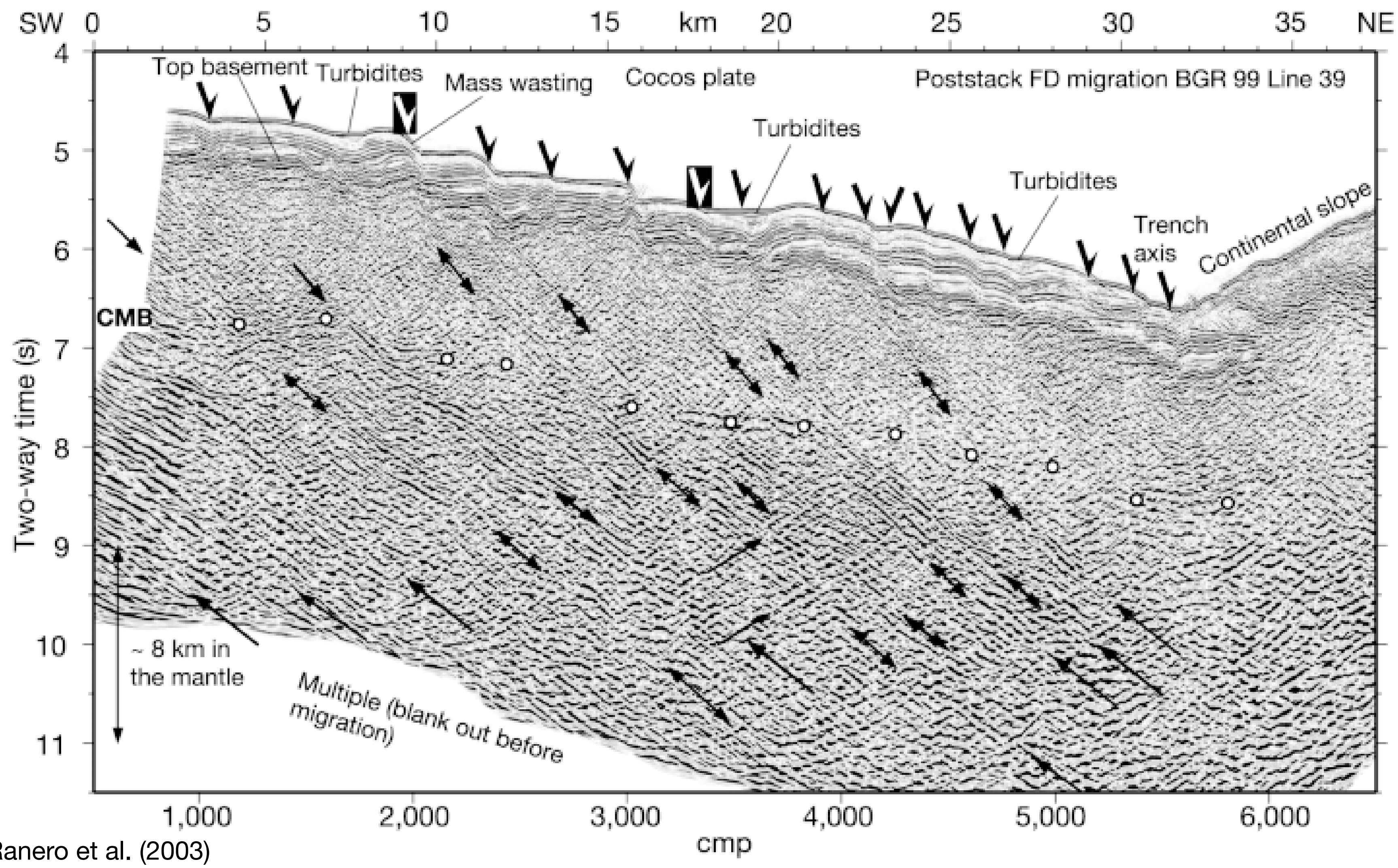


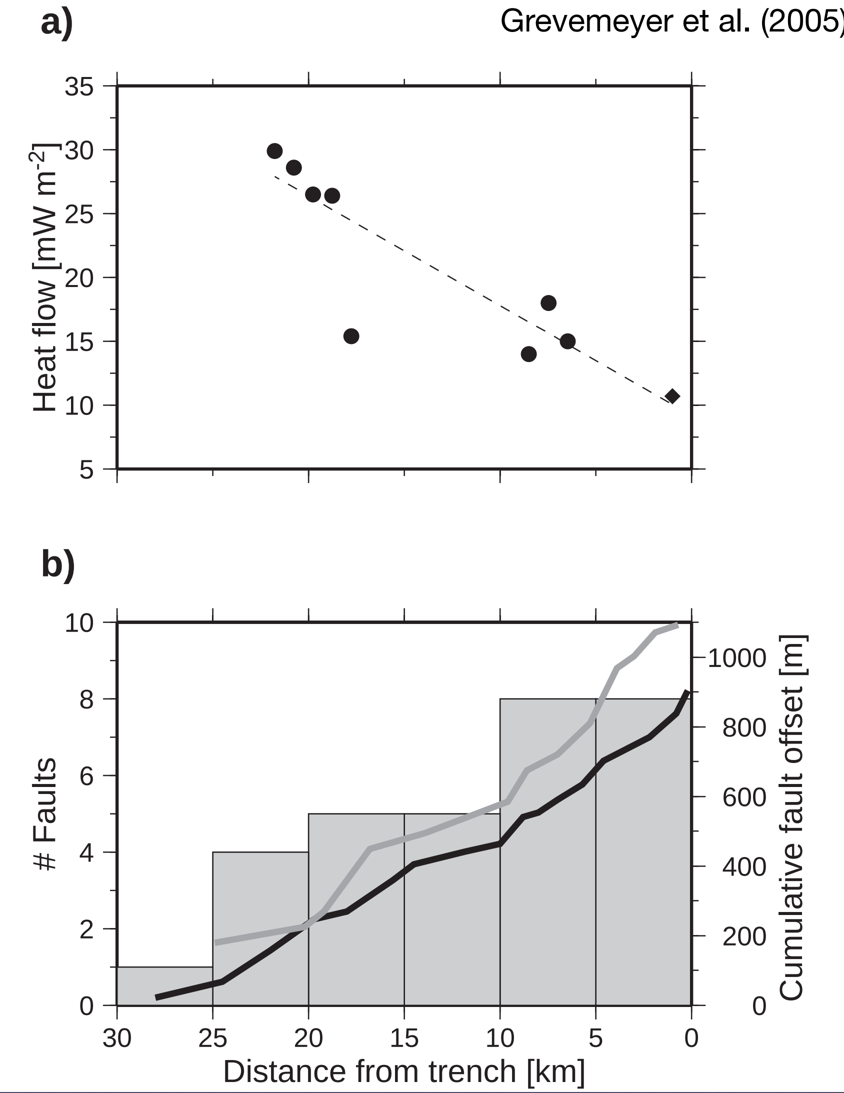
Plate bending



Nicaragua's bending faults

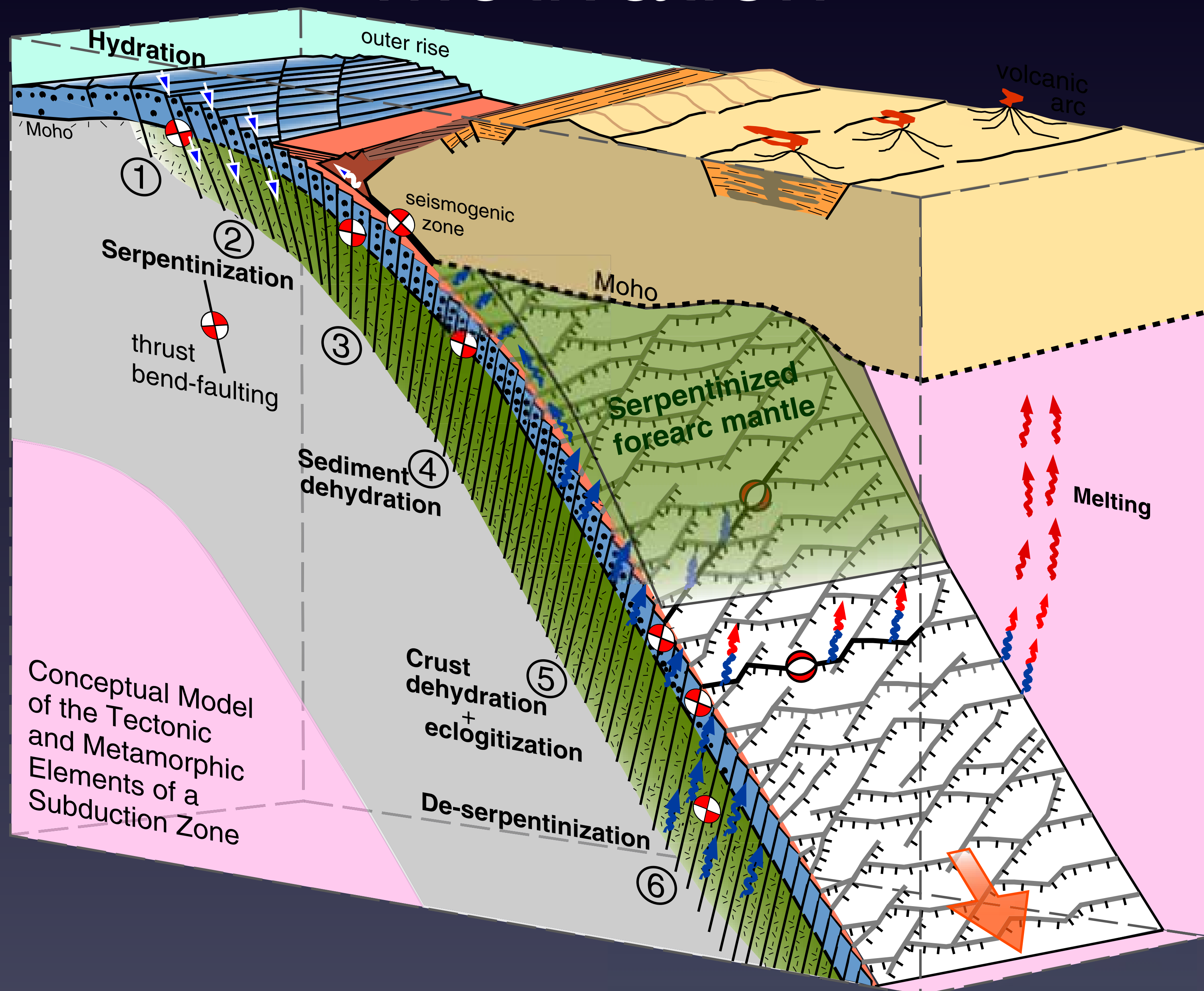


Ranero et al. (2003)



- Mantle penetrating normal faults observed at the Nicaragua outer rise
- Density of faults correlates with decreasing (unusually low) heat flow
- Suggests faults are porous pathways for fluid transport, fueling hydrothermal circulation, hence hydrothermal alteration
- However, no published evidence shows faults are pathways

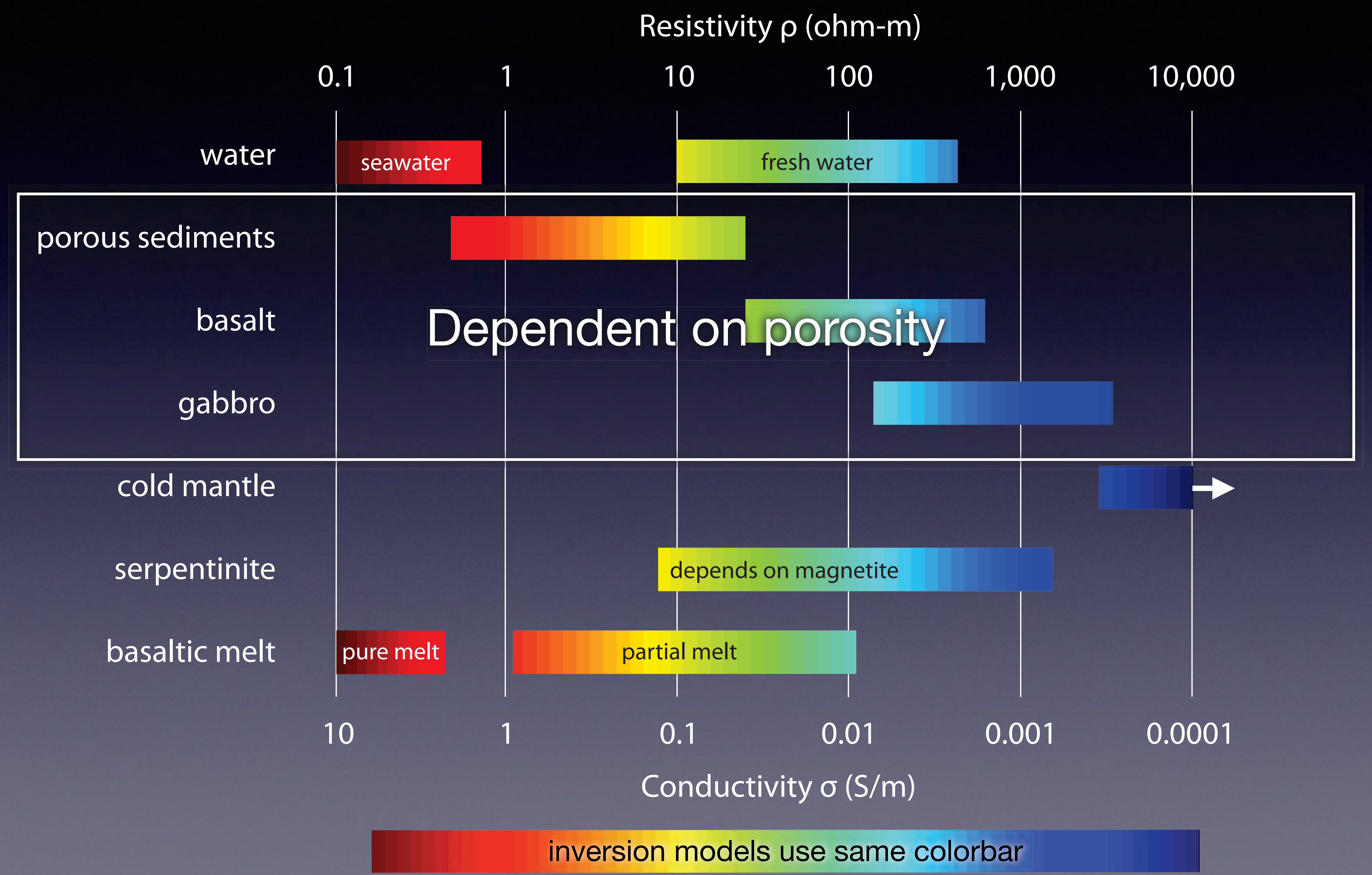
Motivation



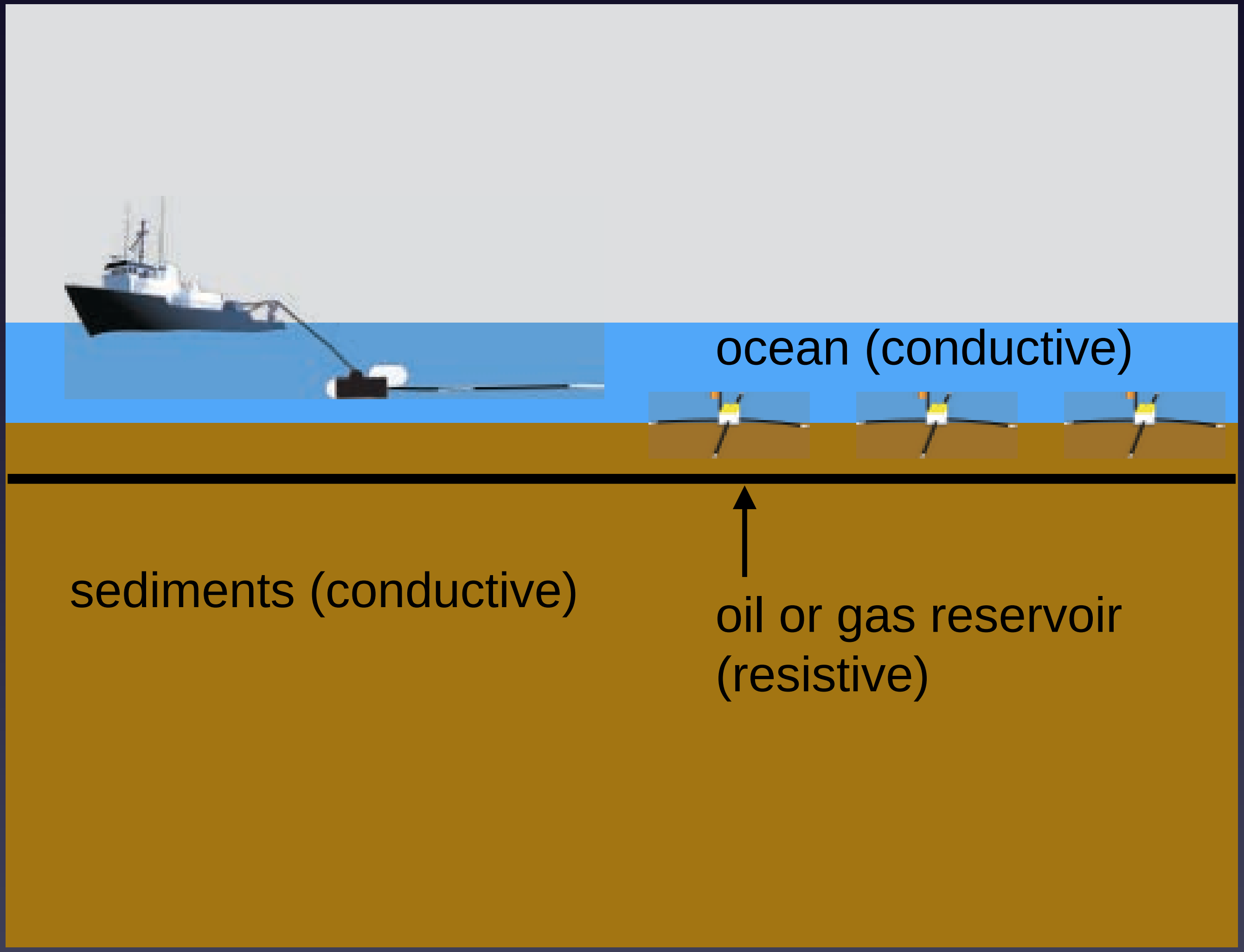
Ranero et al. (2005)

- Mantle penetrating normal faults could provide fluid pathway for serpentinization
- Subducted hydrous minerals become unstable at high pressure/temperature, leading to dehydration reactions that release free water
- Water promotes melting and is critical driver of arc volcanism
- Water weakens the plate interface, modulates megathrust seismicity

Electrical resistivity of oceanic plates



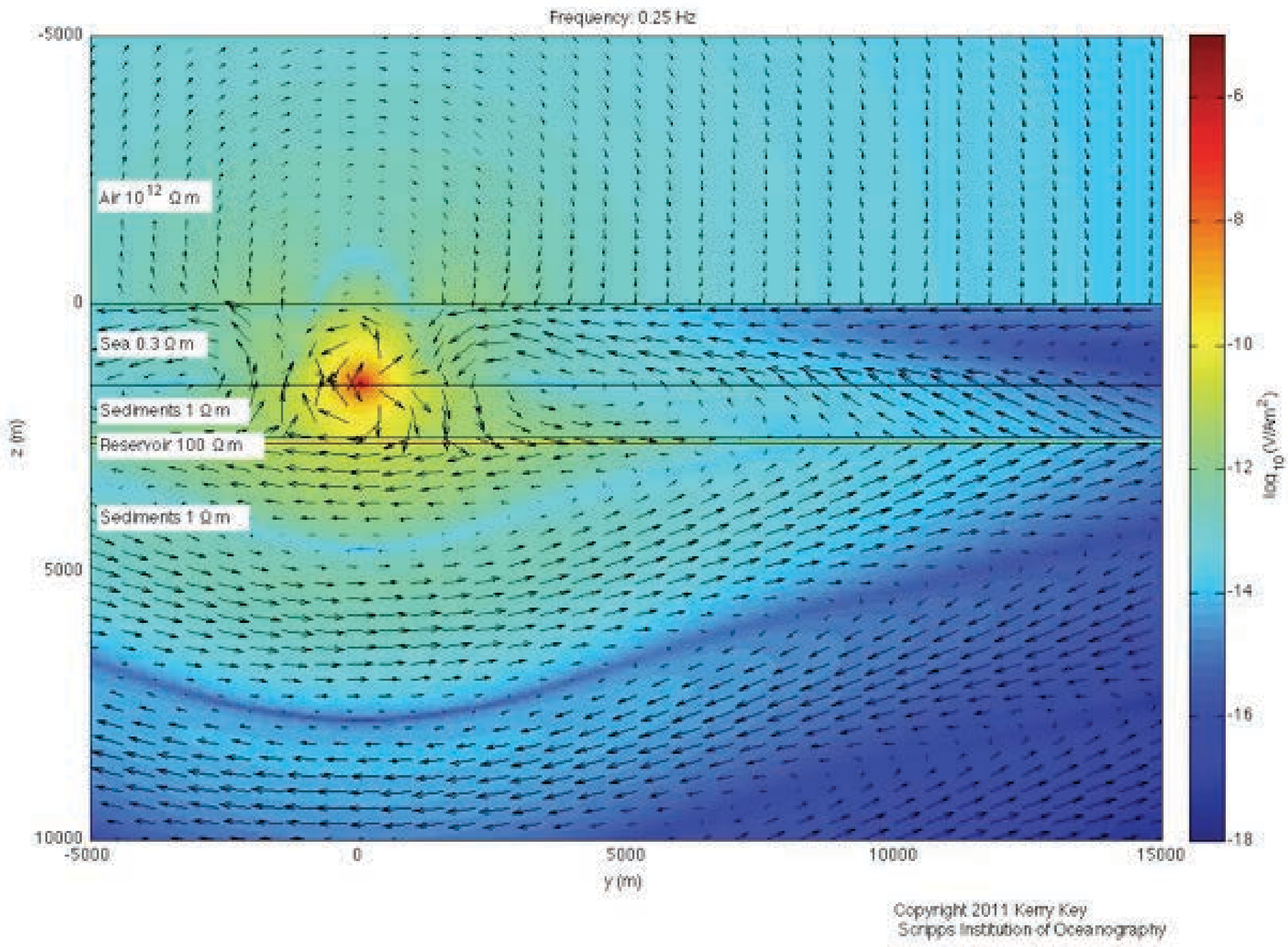
Controlled Source Electromagnetic Method



3D Vector Diffusion Equation: $\nabla \times \nabla \times \mathbf{E} - i\omega\mu\sigma\mathbf{E} = i\omega\mu\mathbf{J_s}$

Frequency Range: 0.1 - 10 Hz

	Resistors	**Conductors**
Attenuation:	Low	High
Phase Velocity:	Fast	Slow



Frequency: 0.25 Hz
Air 10^12 Ω m
Sea 0.3 Ω m
Sediments 1 Ω m
Reservoir 100 Ω m
Sediments 1 Ω m
z (m)
y (m)
log10(V/Am^2)
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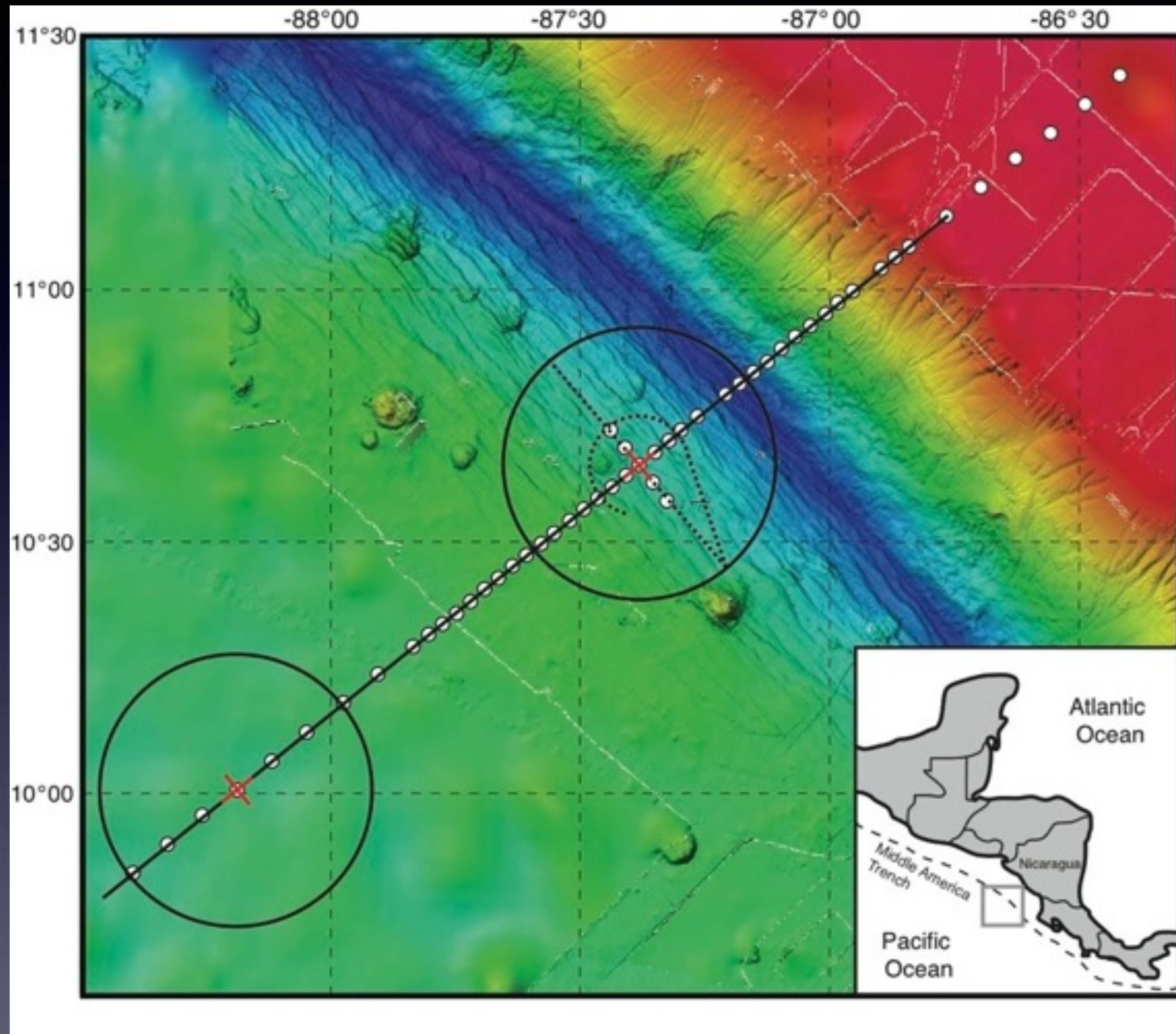
EM Receiver Deployment Movie:

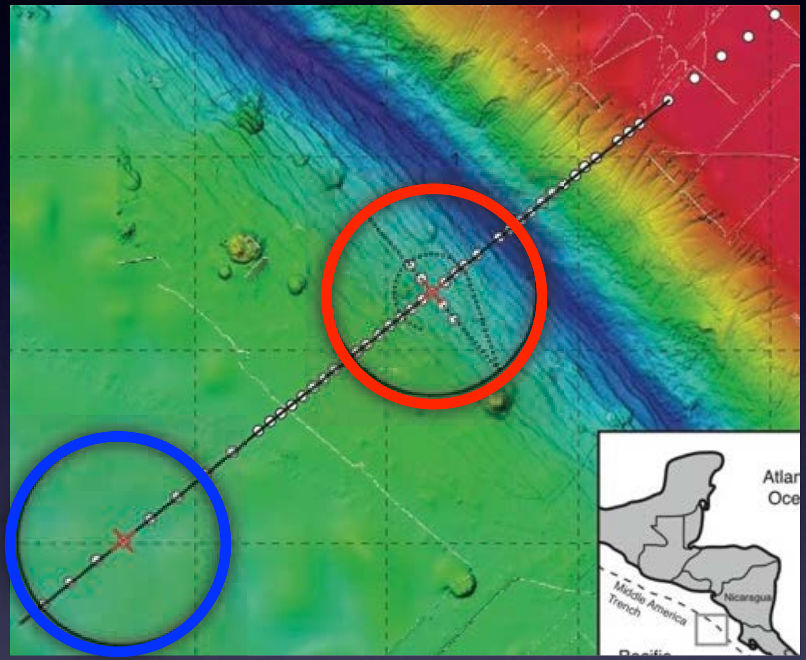
CSEM Transmitter Deployment Movie:

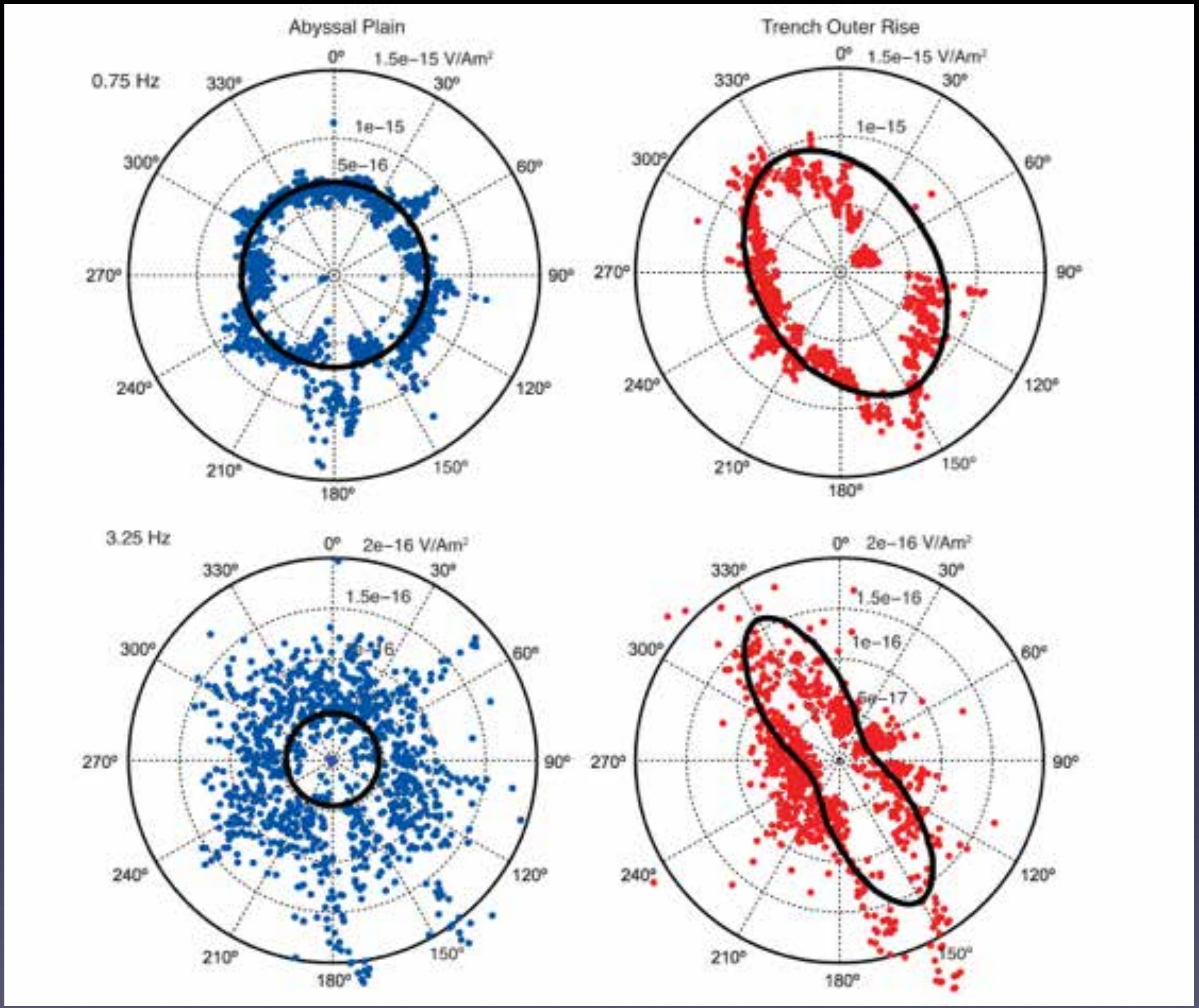
The Serpentinite, Extension and Regional Porosity Experiment Across the Nicaraguan Trench (SERPENT)



- First CSEM survey of a subduction zone
- Single 28 day cruise produced 54 broadband MT / EM stations
- 4 long-wire EM (LEM) receiver deployments
- 800 km of CSEM tows
- 96% data recovery rate

Results from Anisotropy Circles

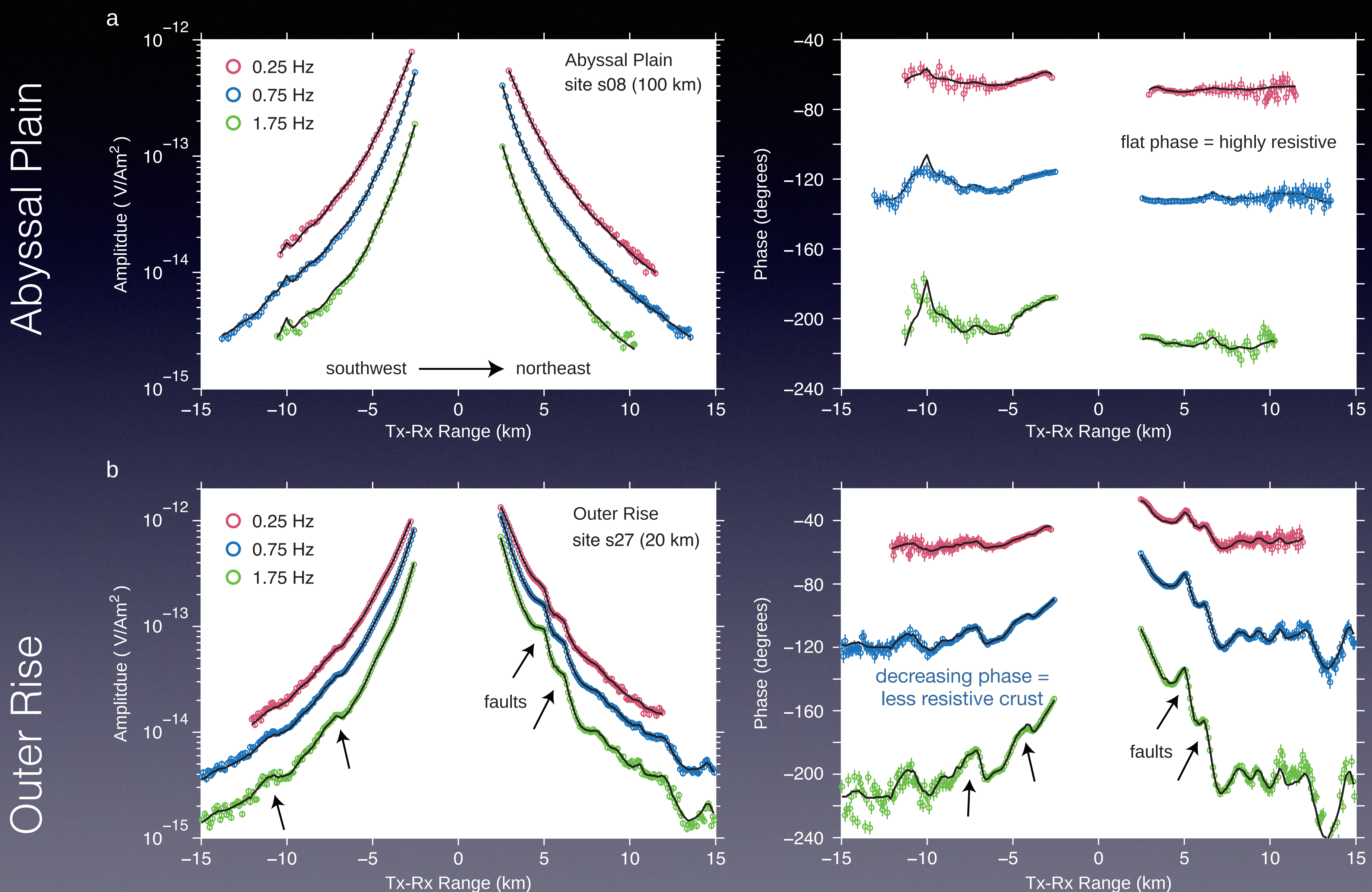




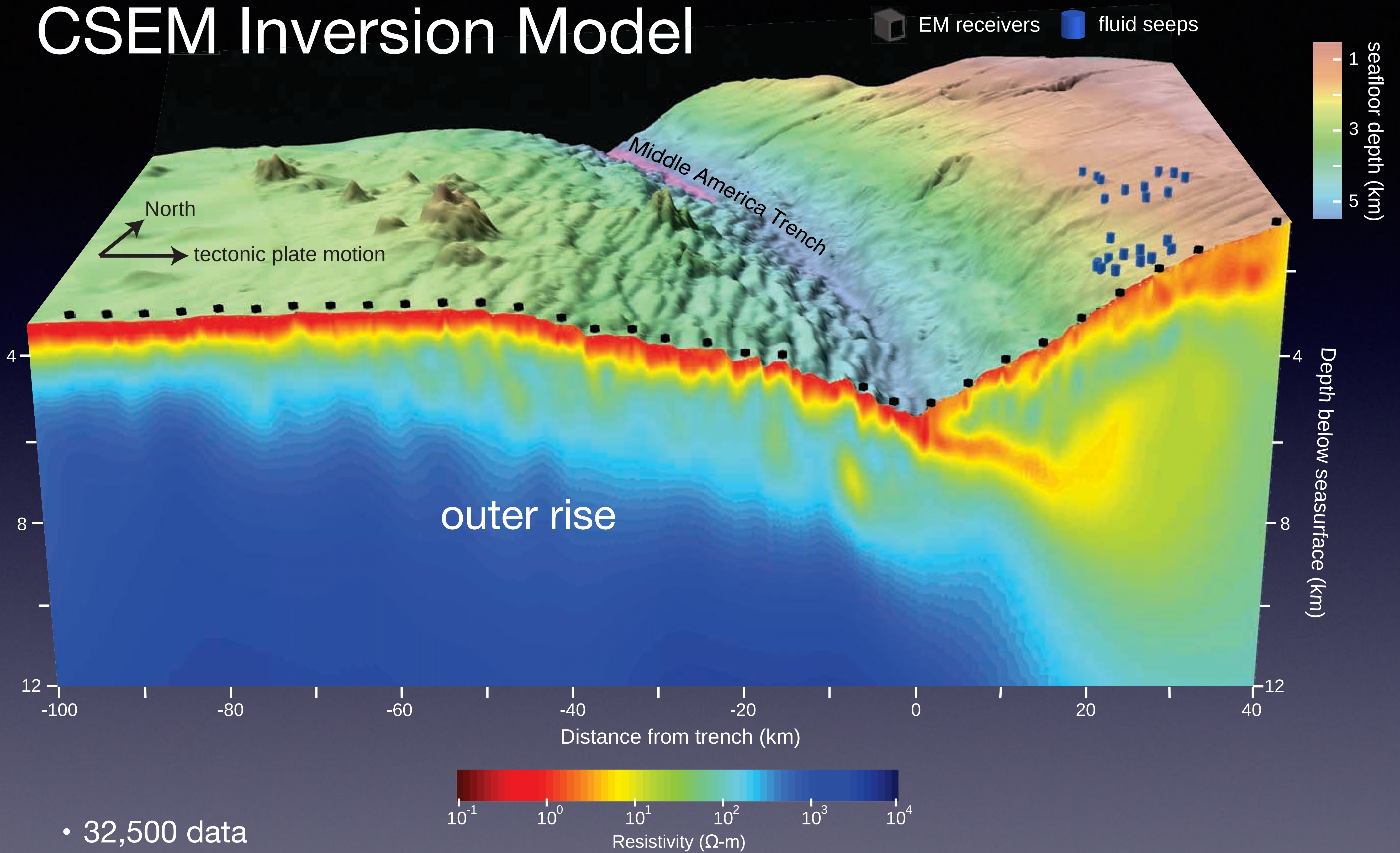
- Polarization ellipse maxima show anisotropic fabric aligned with faults
- Anisotropy significantly stronger beneath the outer rise
- **Data well fit with fault parallel conductive plates, 5:1 anisotropy**

Key, K., S. Constable, T. Matsuno, R. L. Evans, and D. Myer (2012), Electromagnetic detection of plate hydration due to bending faults at the Middle America Trench, Earth Planet Sc Lett, 351-352, 45–53.

CSEM Data Examples

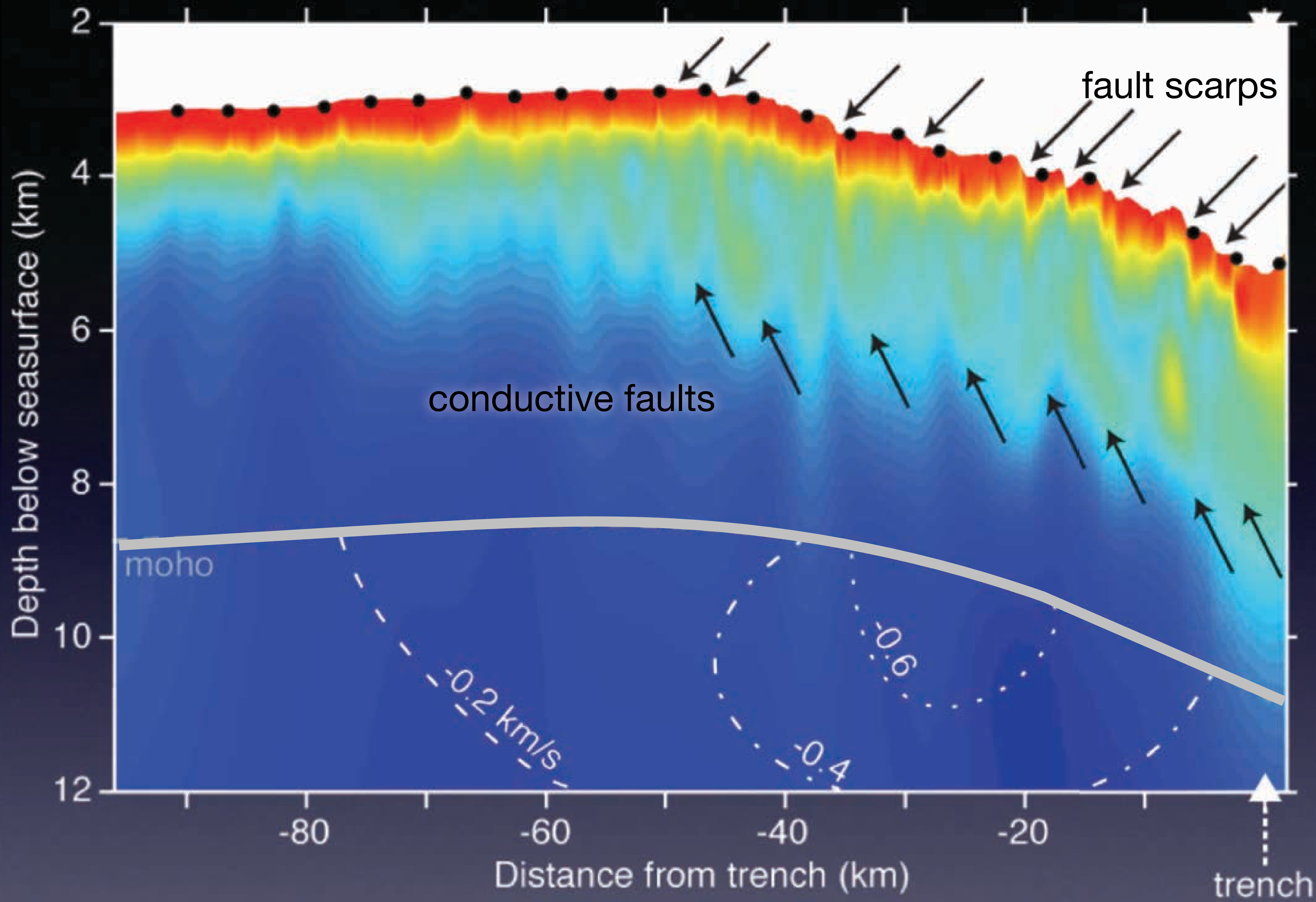


CSEM Inversion Model



- 32,500 data
- 28,000 model parameters
- Regularized non-linear inversion with adaptive finite element forward solver
- Fit to RMS 1.0 with 2% error floor
- Ran on 320 processors for 16 hours

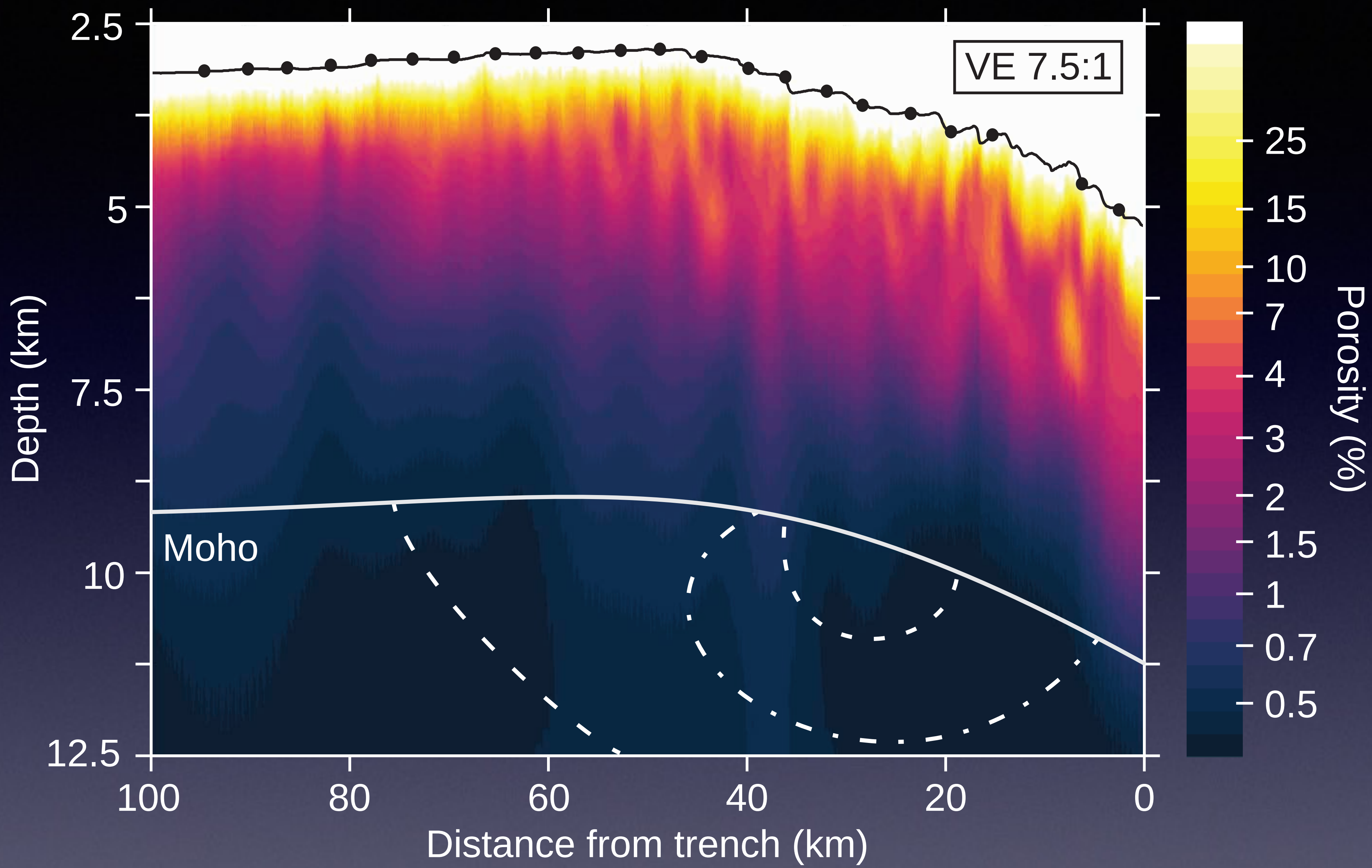
Outer rise



- Dashed lines: P-wave velocity anomalies from Ivandic et al. (2008)
- Fault scarps correlate with steeply dipping conductive channels
- Porous channels along the fault traces drive fluids into the slab
- Mantle stays resistive

Naif, S., K. Key, S. Constable, and R. L. Evans (2015), Water-rich bending faults at the Middle America Trench, *Geochem Geophy Geosy*, *16*(8), 2582–2597.

Porosity Estimated from Resistivity



Archie's Law:

$$\rho = \rho_f \phi^{-m}$$

- ρ: bulk resistivity
- ρ_f: fluid resistivity
- ϕ: porosity
- m: cementation exponent

m = 2.0

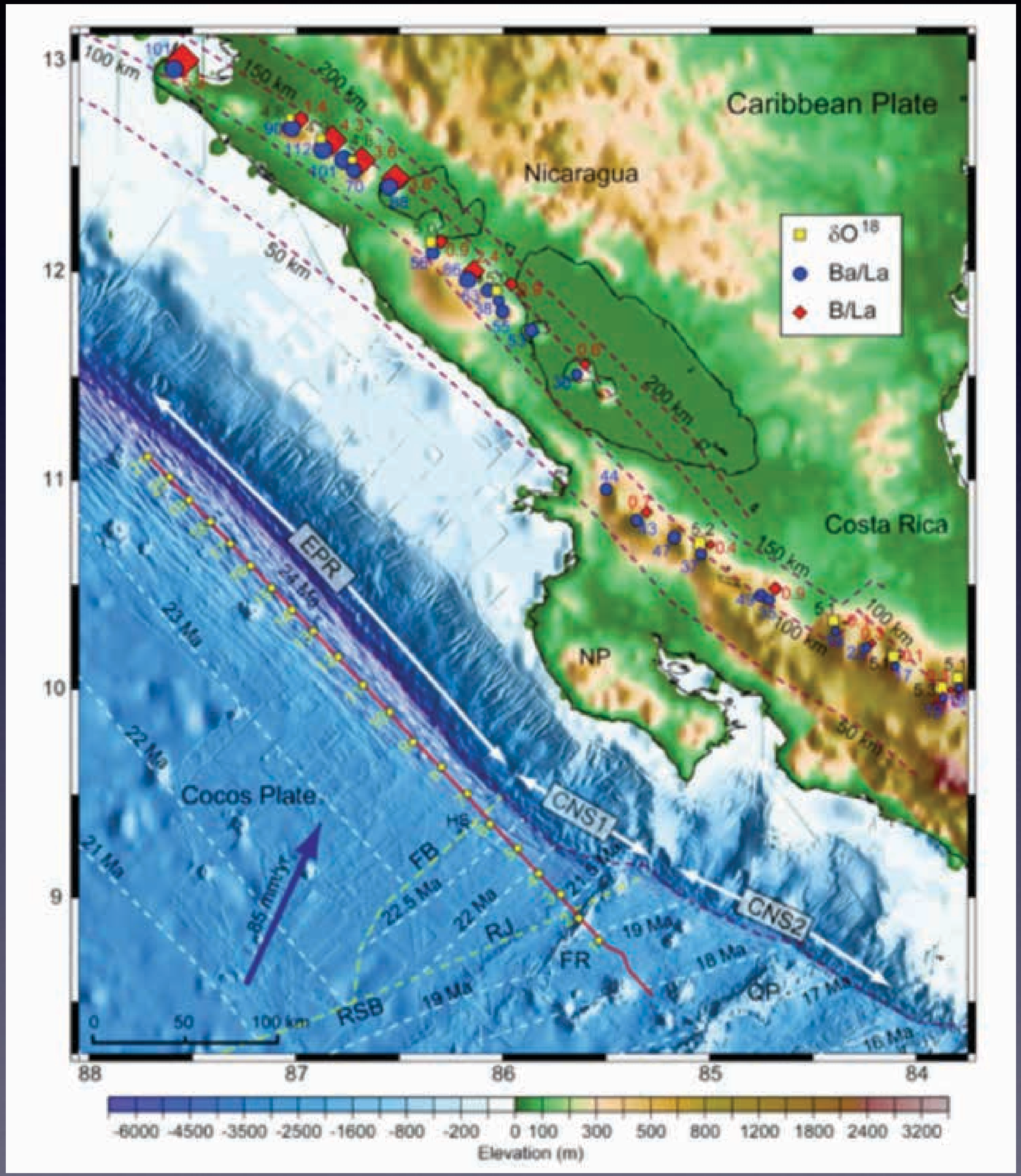
Porosity Evolution with Plate Bending

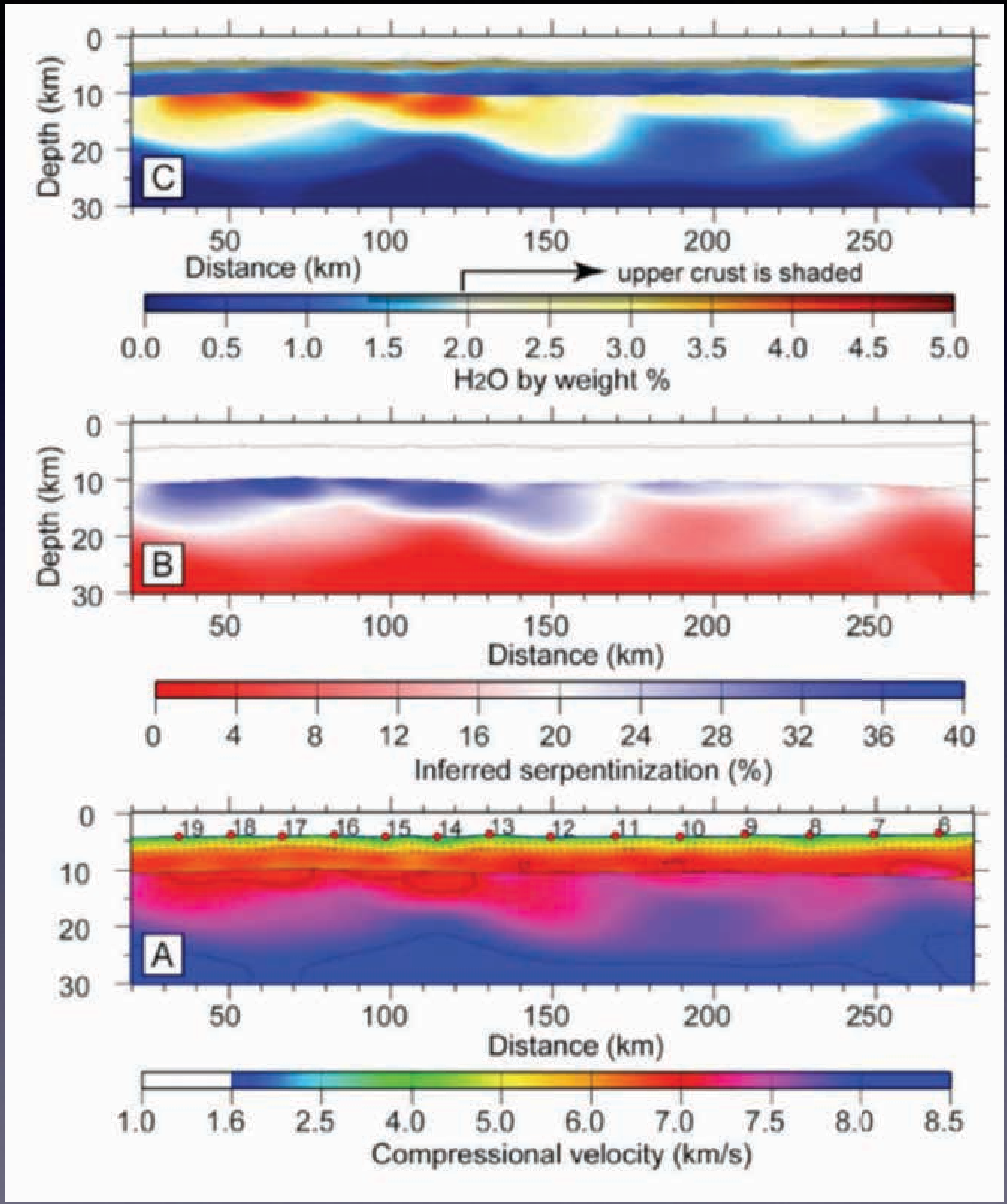
Distance from trench	Extrusives, m= 2	Dikes, m= 2	Gabbros, m= 2
24 Ma crust*	10.4	3	0.7
80-100 km	12.2	2.7	0.7
40-60 km	13.5	4.7	1.3
5-20 km	14.3	4.8	1.7

* from Jarrard's (2003) ocean drilling compilation study

- Crustal porosity increases 60%, <u>doubles</u> in the lower crust
- Significantly more crustal pore water is subducted than previously thought

Seismic evidence for uppermost mantle serpentinization



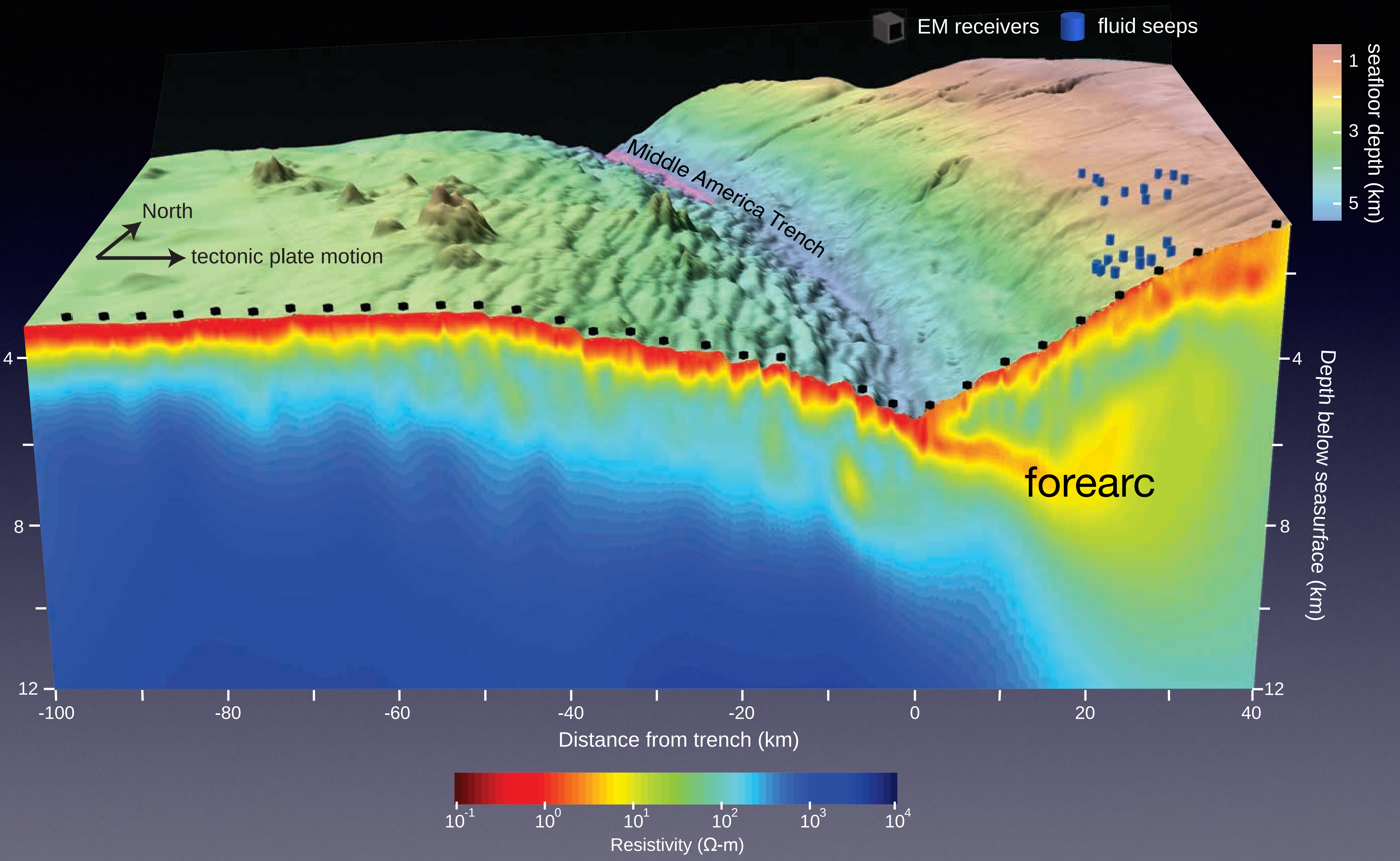


van Avendonk et al (2011)

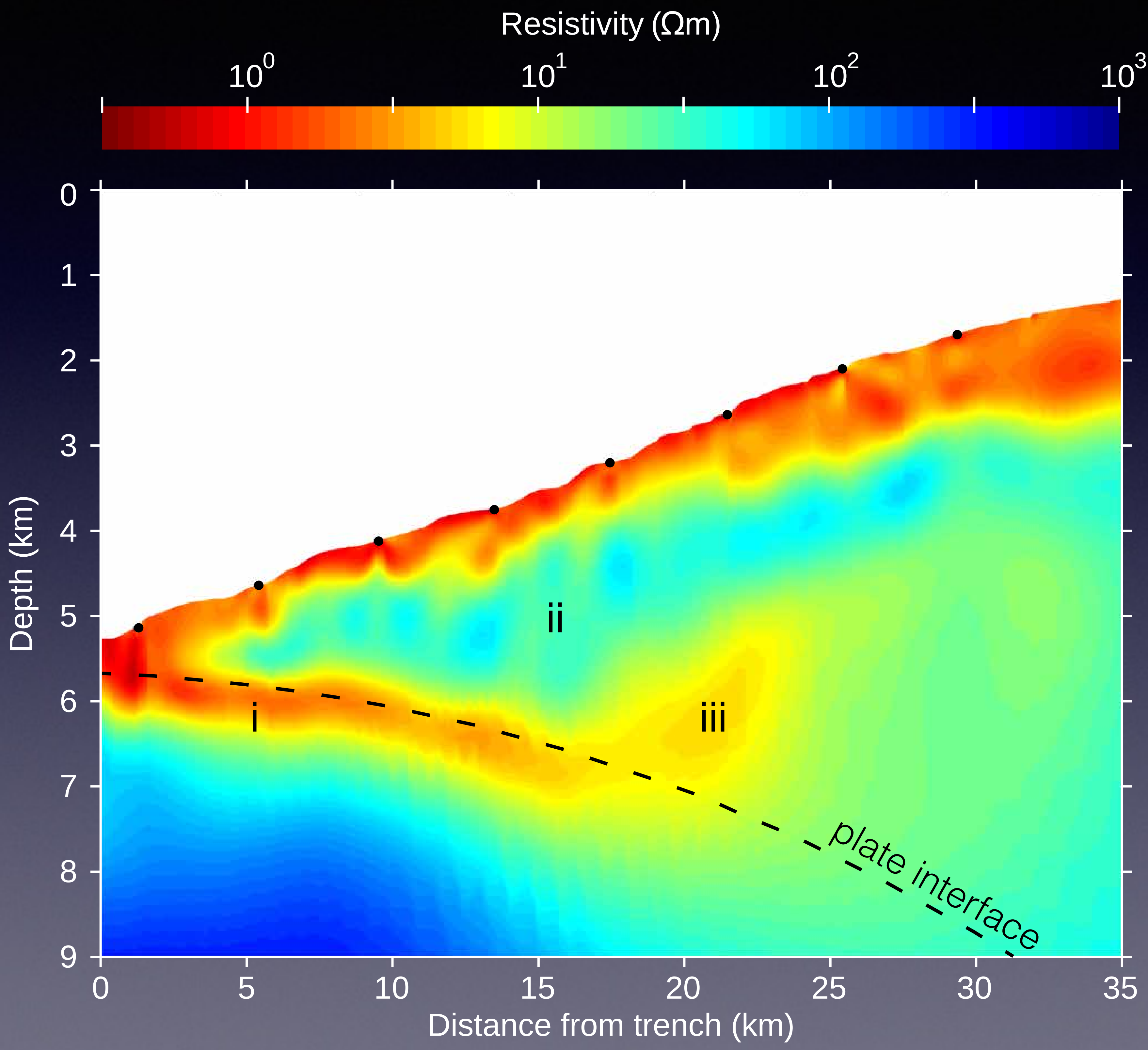
Outer Rise Summary:

- Bending faults are porous fluid pathways
- More pore water subducts than previously thought
- Crust is heterogeneously hydrated
- Mantle remains resistive
    - seismic data requires significant serpentinization
    - high resistive compatible with low magnetite content, implies low degree of serpentinization (<15%)

CSEM Inversion Model



Forearc Resistivity



i. Sediment subduction along megathrust plate interface

ii. Resistive upper plate is low porosity, consistent with basement rock

iii. Conductor penetrates upper plate

Sediment Subduction

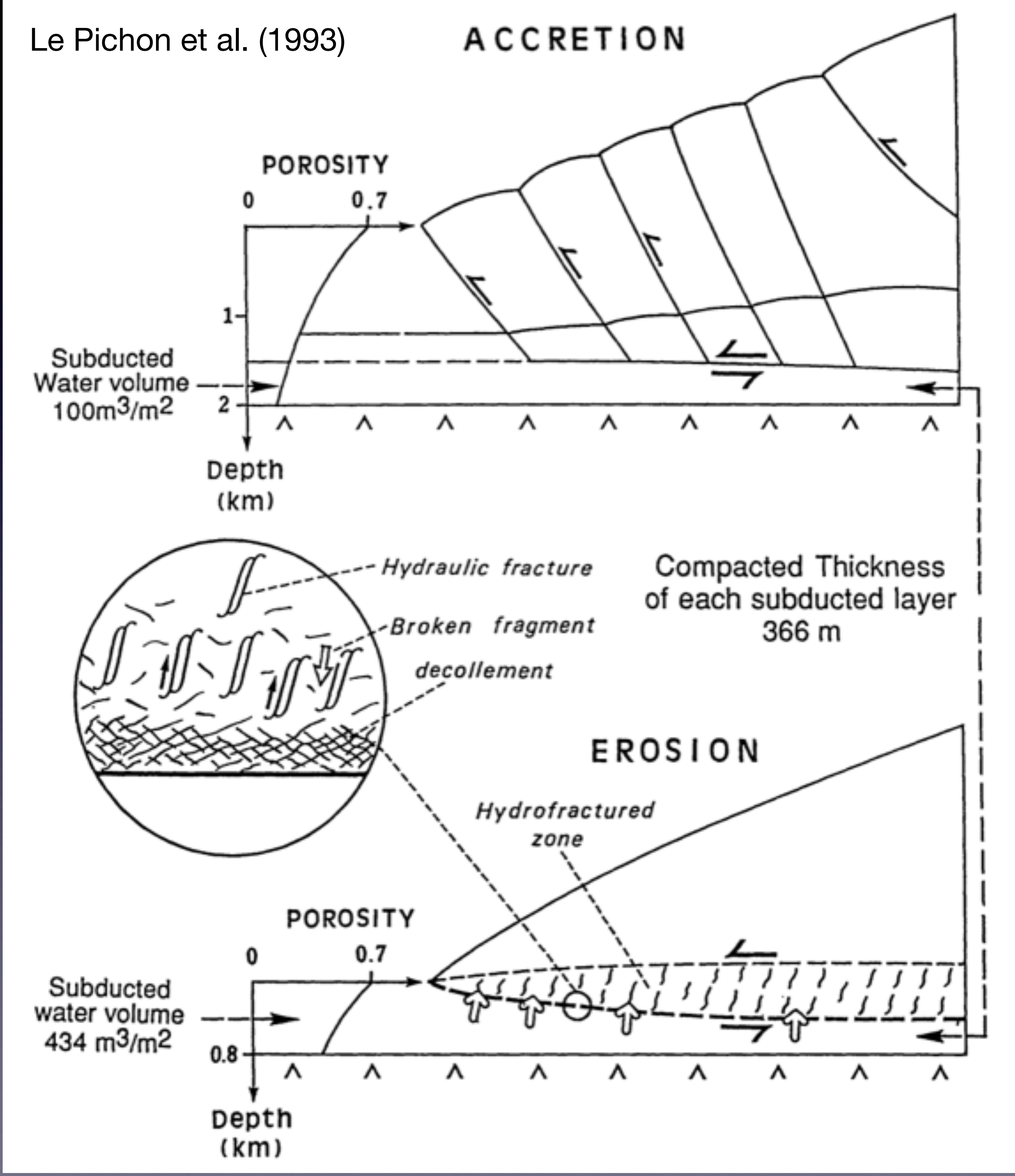
Accreting Margin:

- thicker sediments on incoming plate
- most sediments accreted onto margin
- compacted deeper sediments subducted
- **less water subducted**

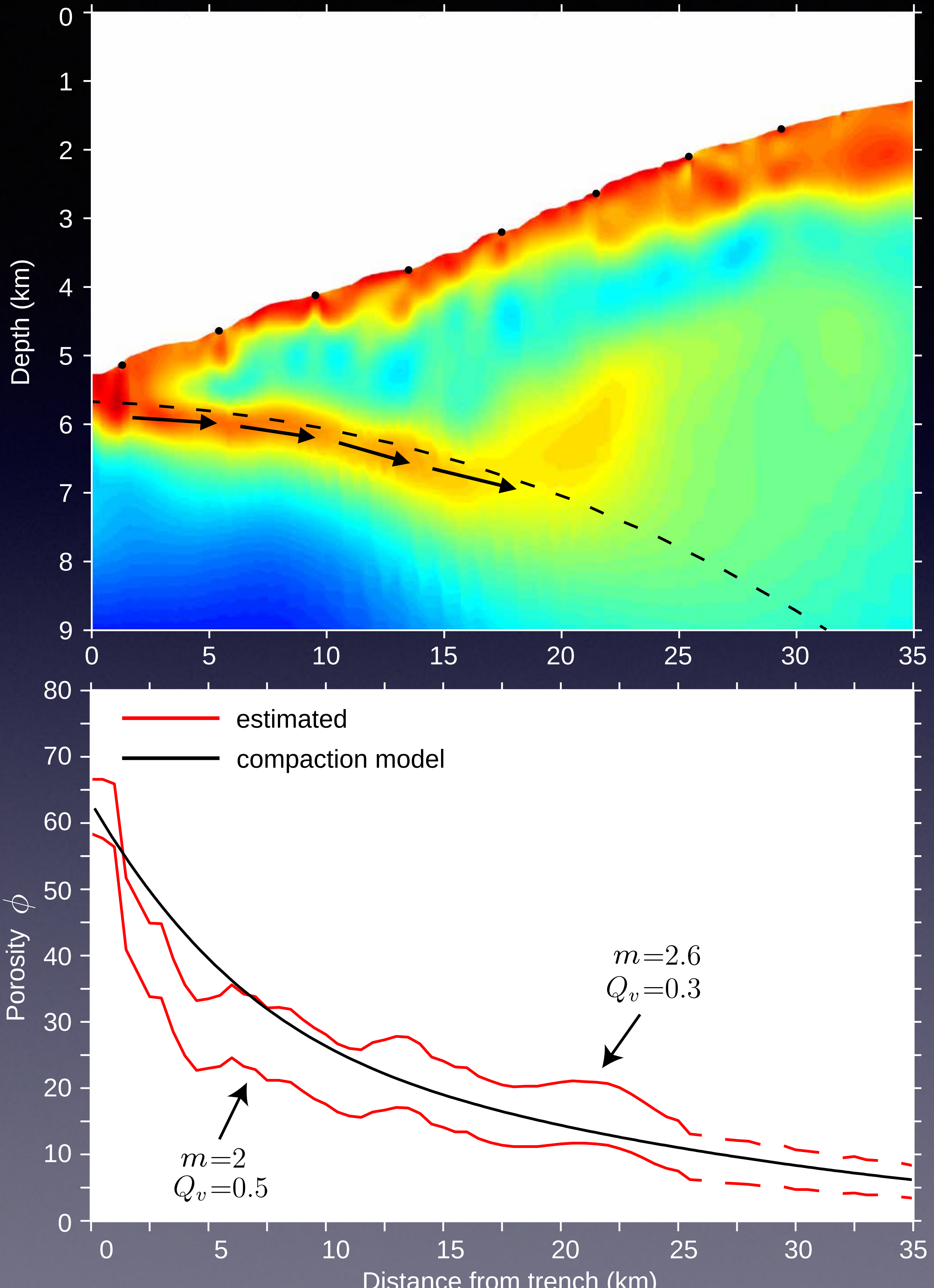
Non-accreting Margin:

- thinner sediments on incoming plate
- all sediments subducted
- sediments have higher porosity
- **more water subducted**

<u>Nicaragua is non-accreting</u>



Subducted sediment porosity



- Porosity estimated with an empirical relationship that accounts for surface conduction in clays

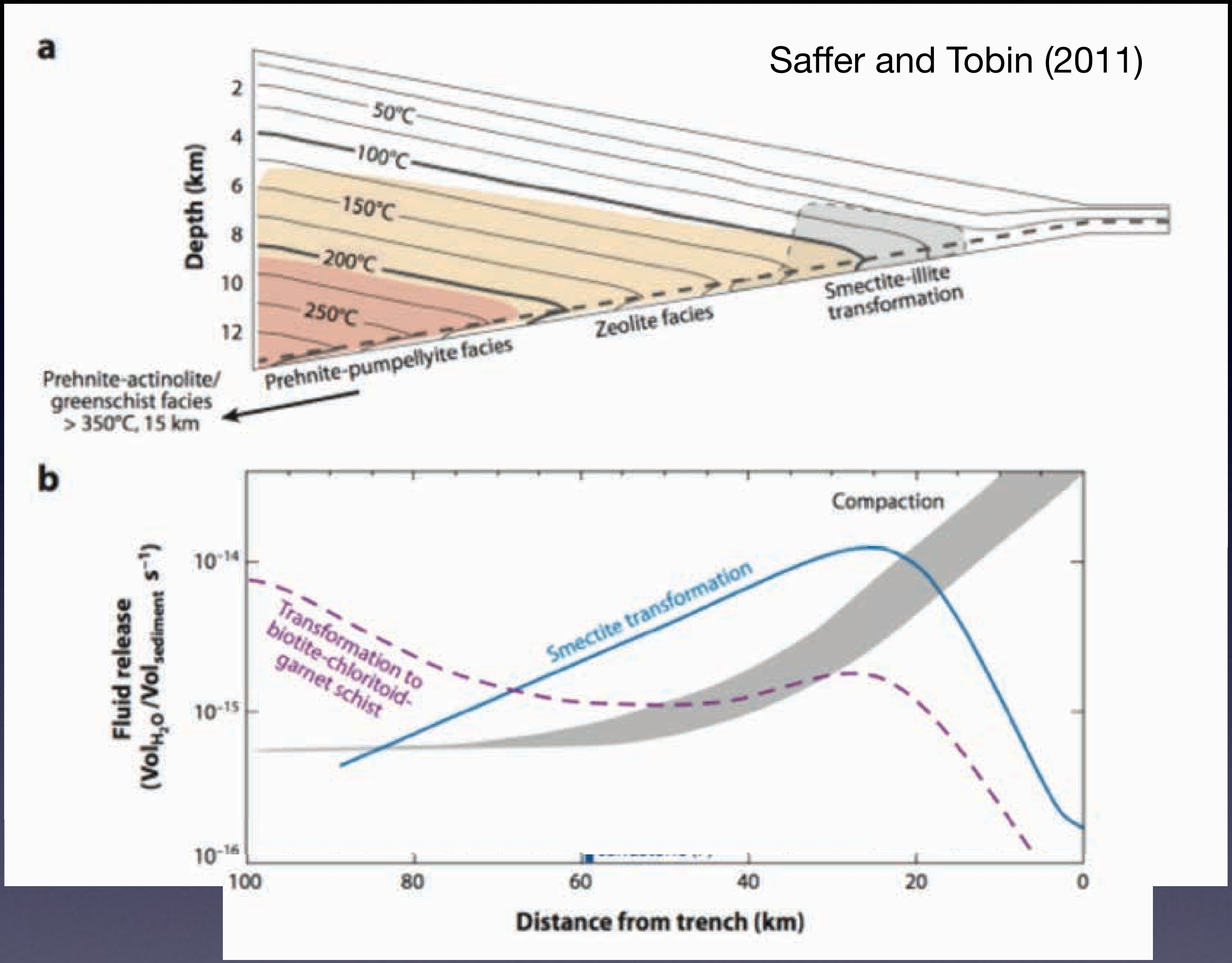
  (Sen & Goode, 1998)

- Compaction model from lab studies and drilling data:

  (Spinelli et al., 2006; Bray & Karig, 1985)

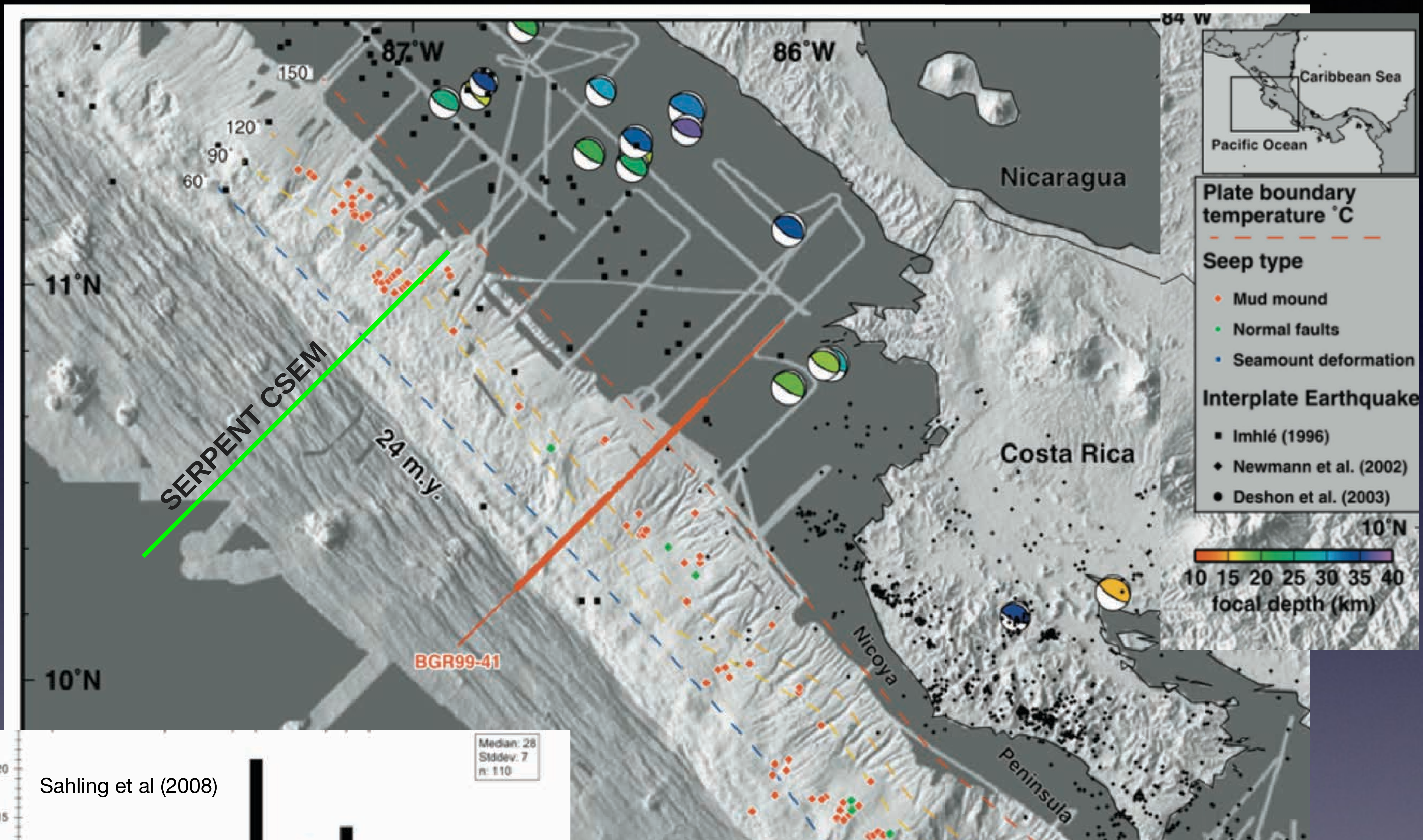
$$\phi = 0.772e^{-0.579z}$$

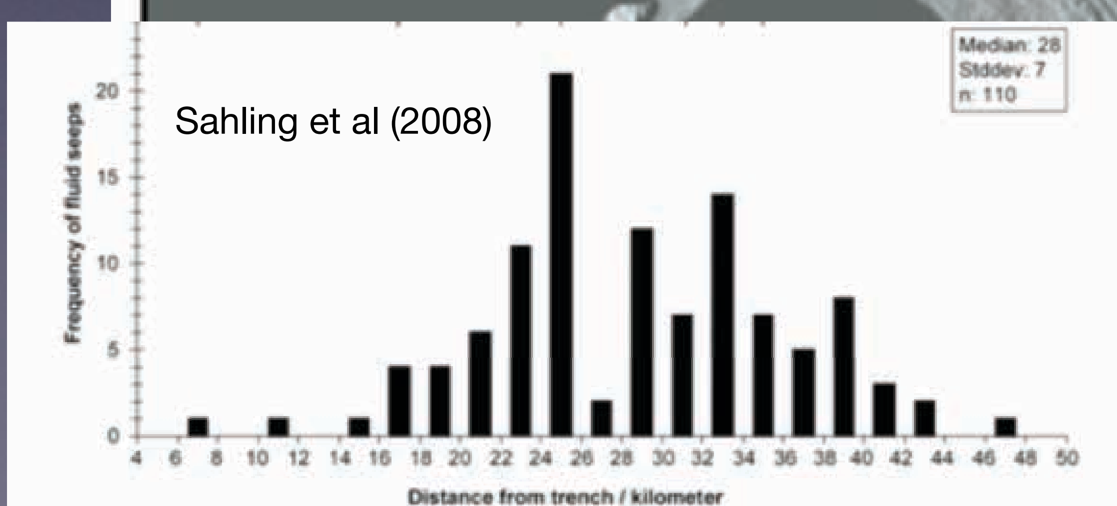
Additional fluids from clay transformation



- Example for Nankai Trough
- Compaction is largest source of fluids in first 20 km
- Clay transformation is largest source of fluids beyond 20 km

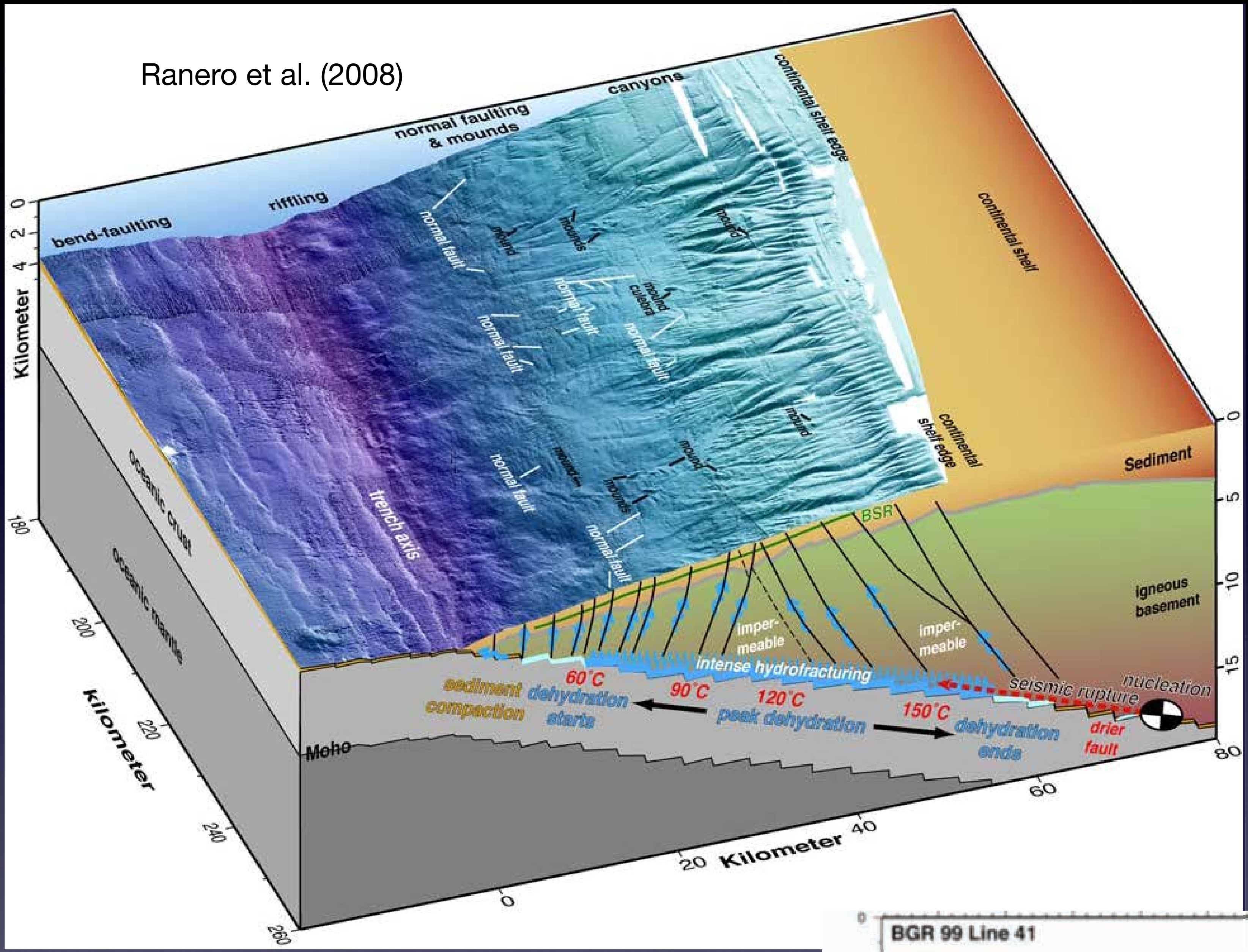
Abundant seeps 20-40 km from trench axis

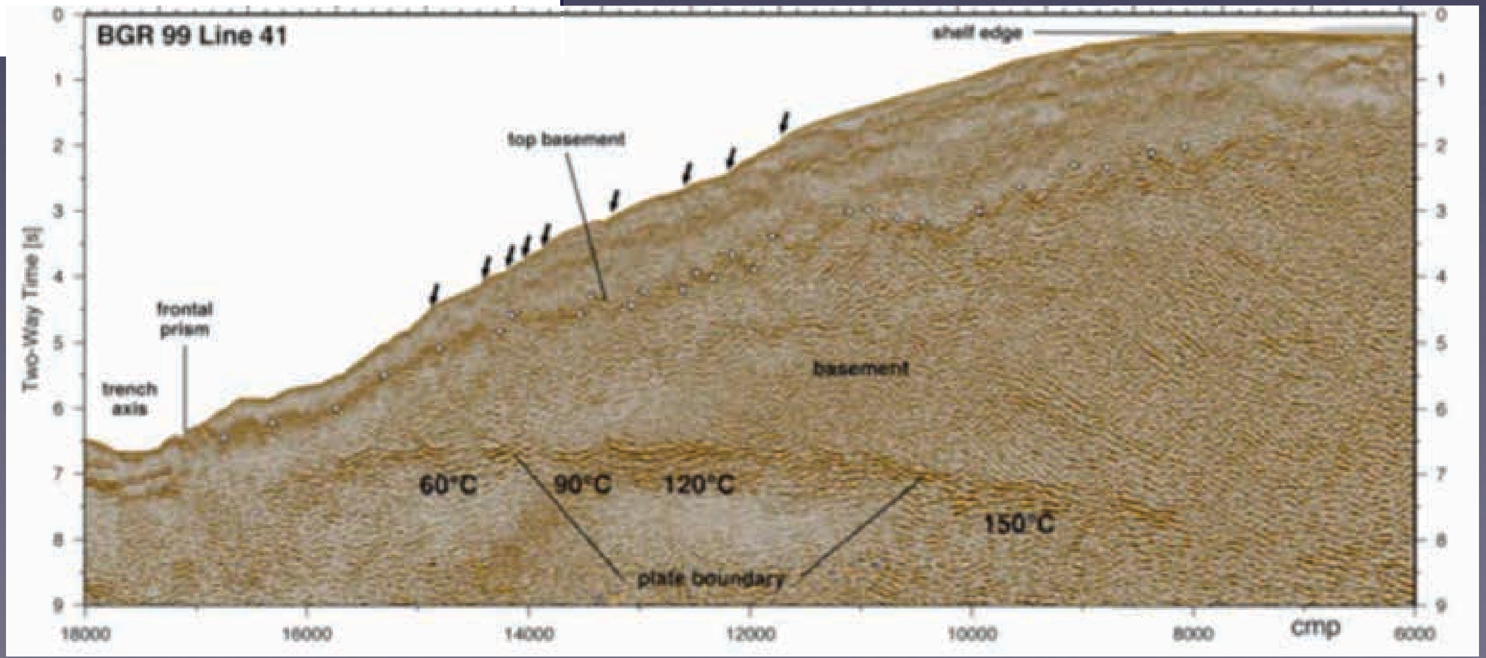




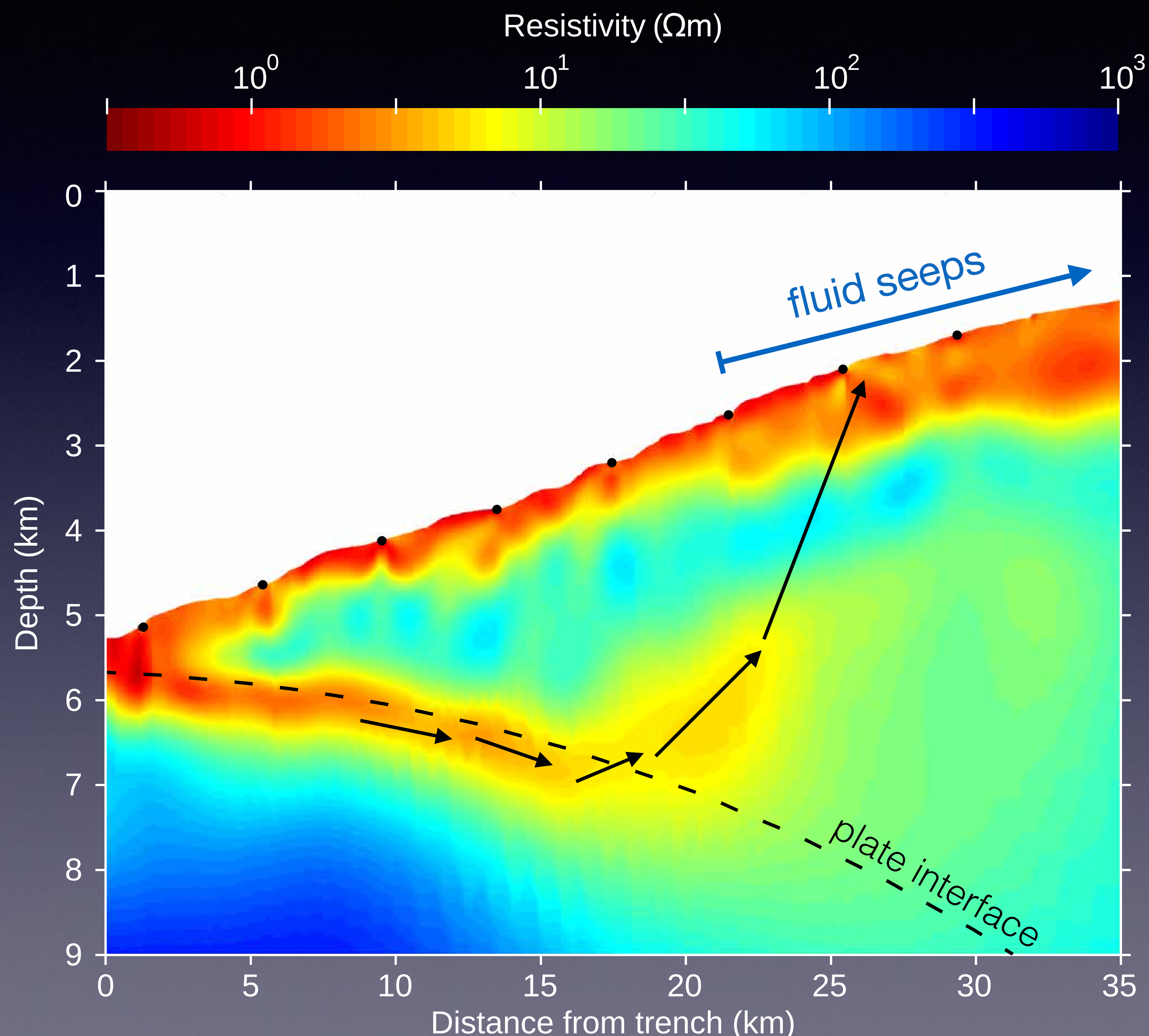
Ranero et al. (2008)

Conceptual model of shallow forearc fluid processes

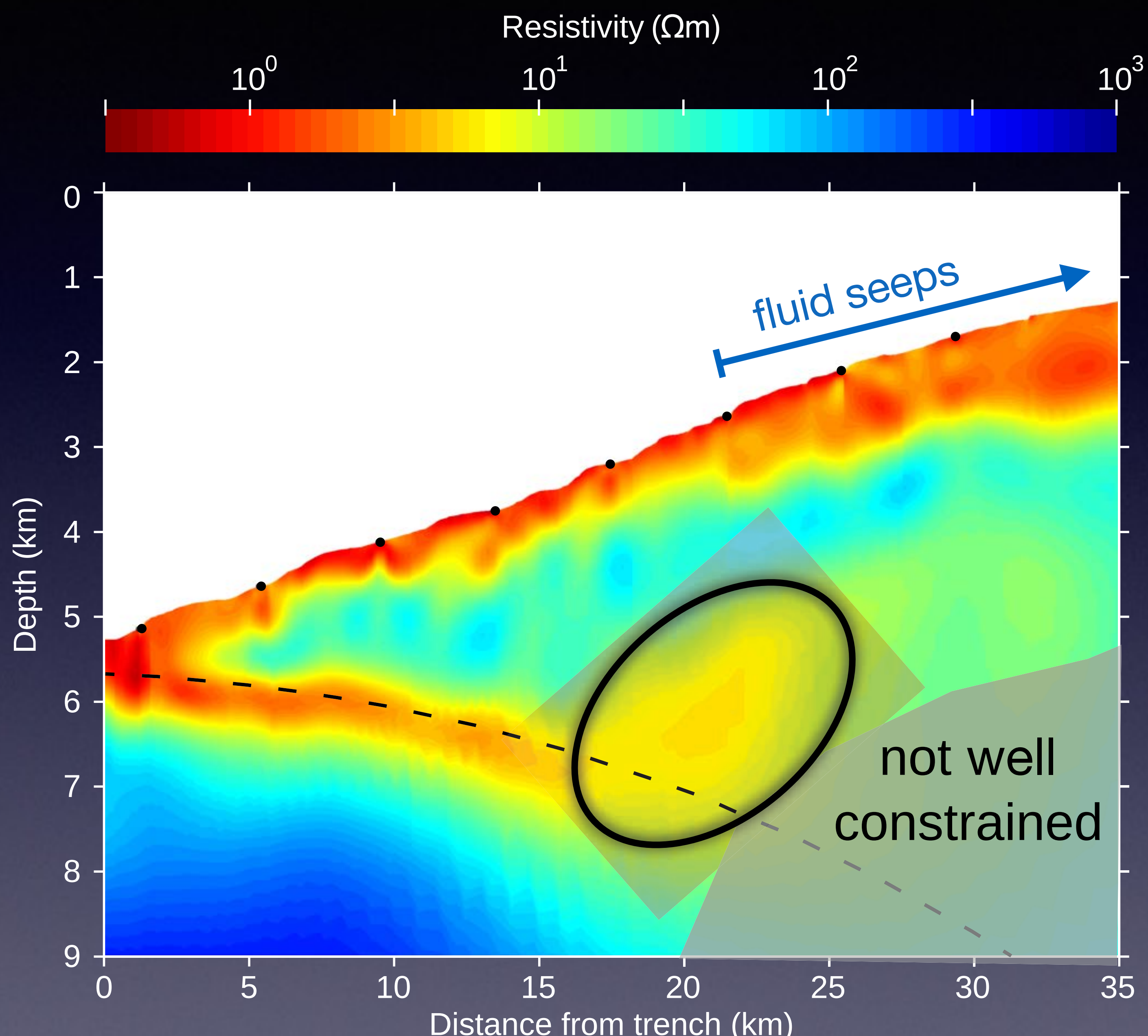




Conductor above plate interface: porous pathway for fluid transport?

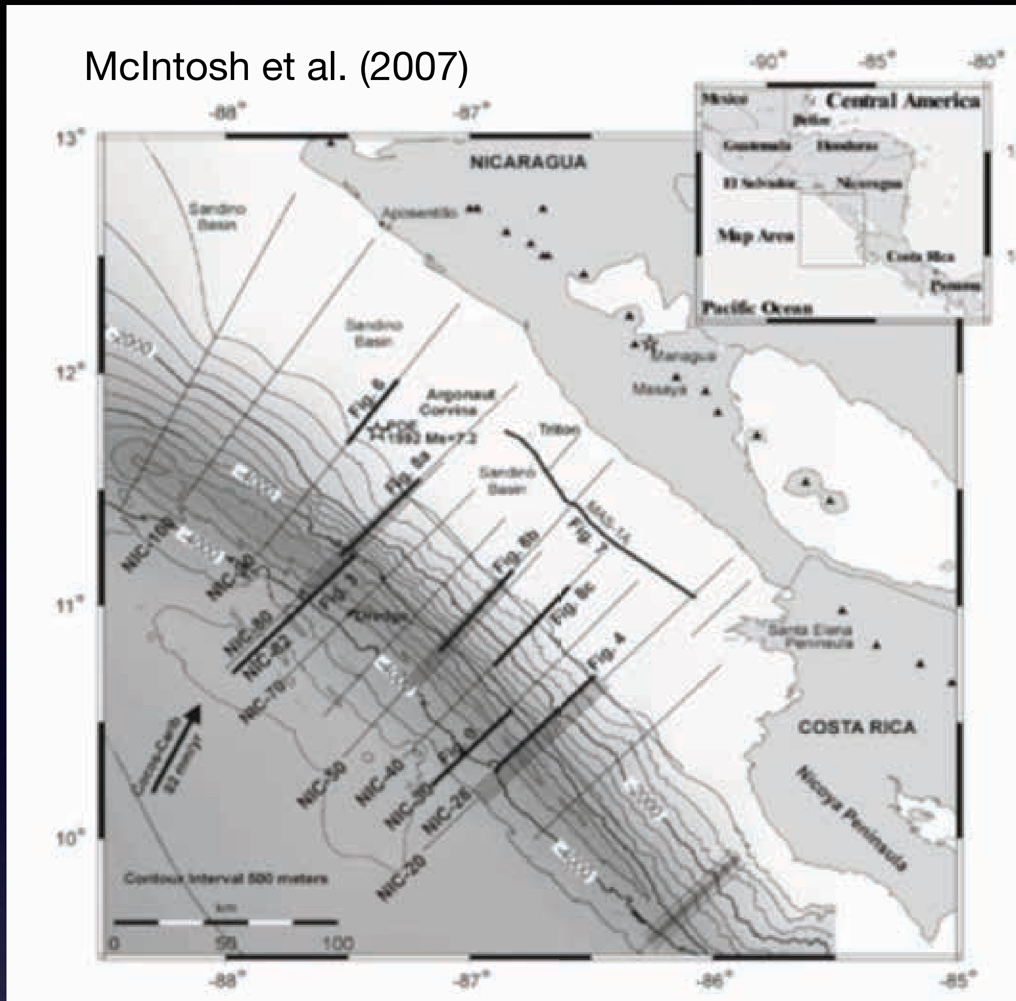


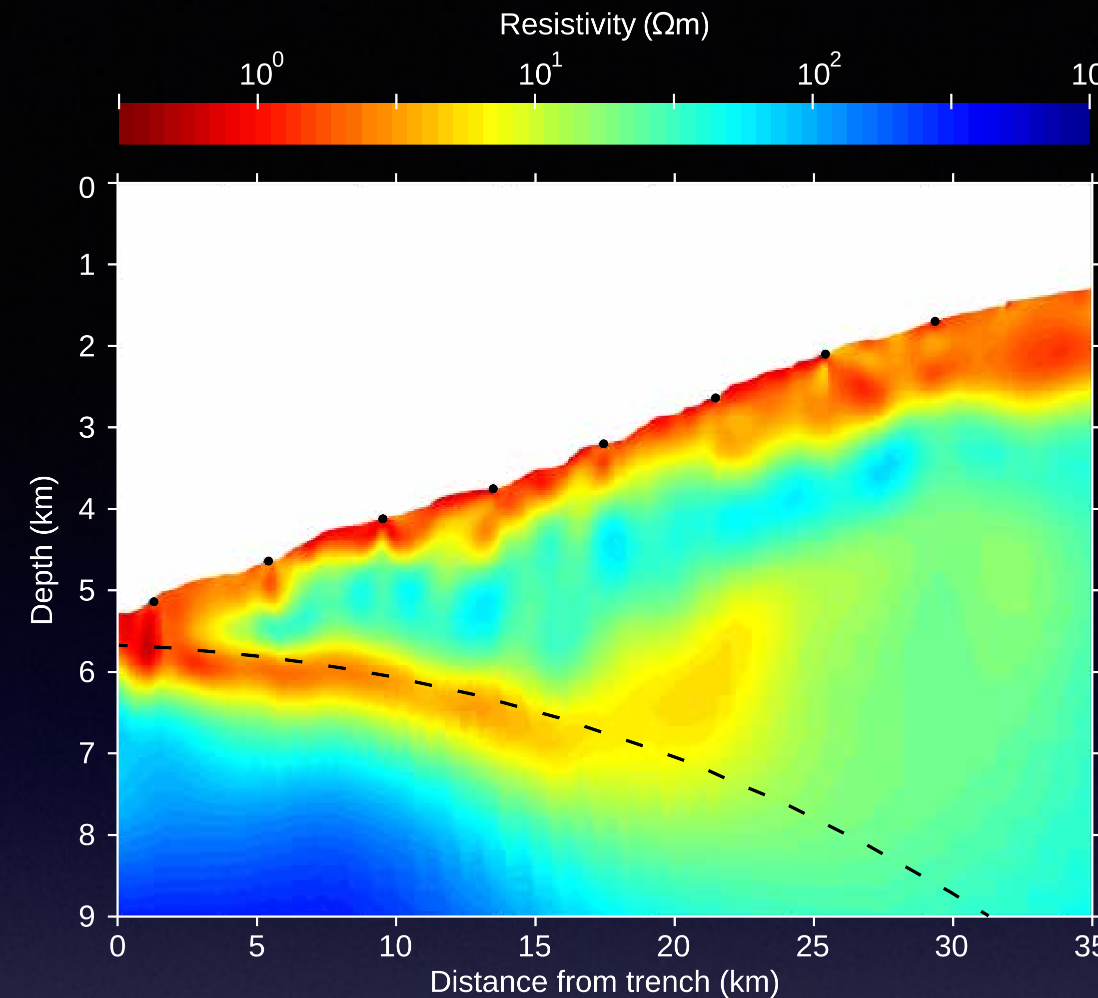
Conductor above plate interface - what is it?

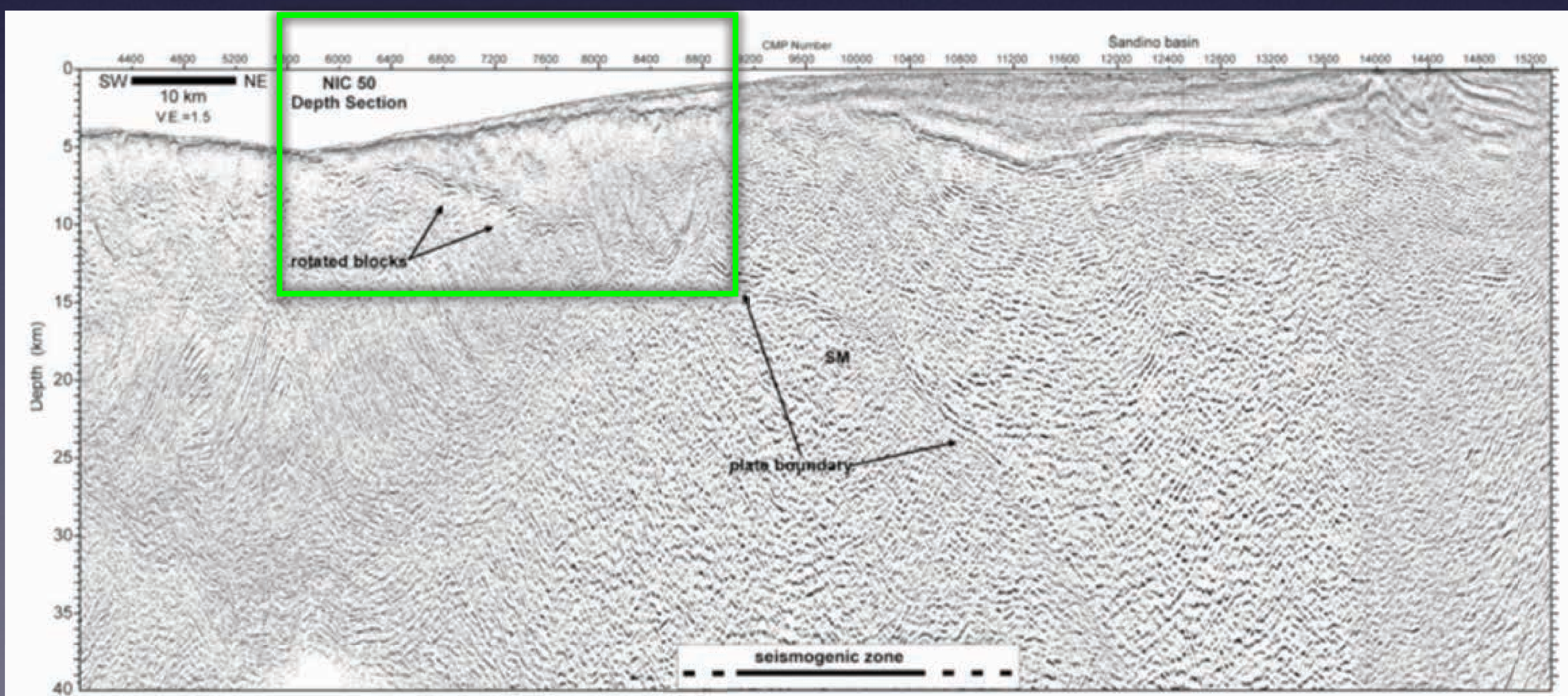


- **Underthrust sediments?**
  - uplift
- **Subducted seamount?**
  - no evidence in bathymetry
- Locus of persistent **hydrofracturing?**
  - subsidence

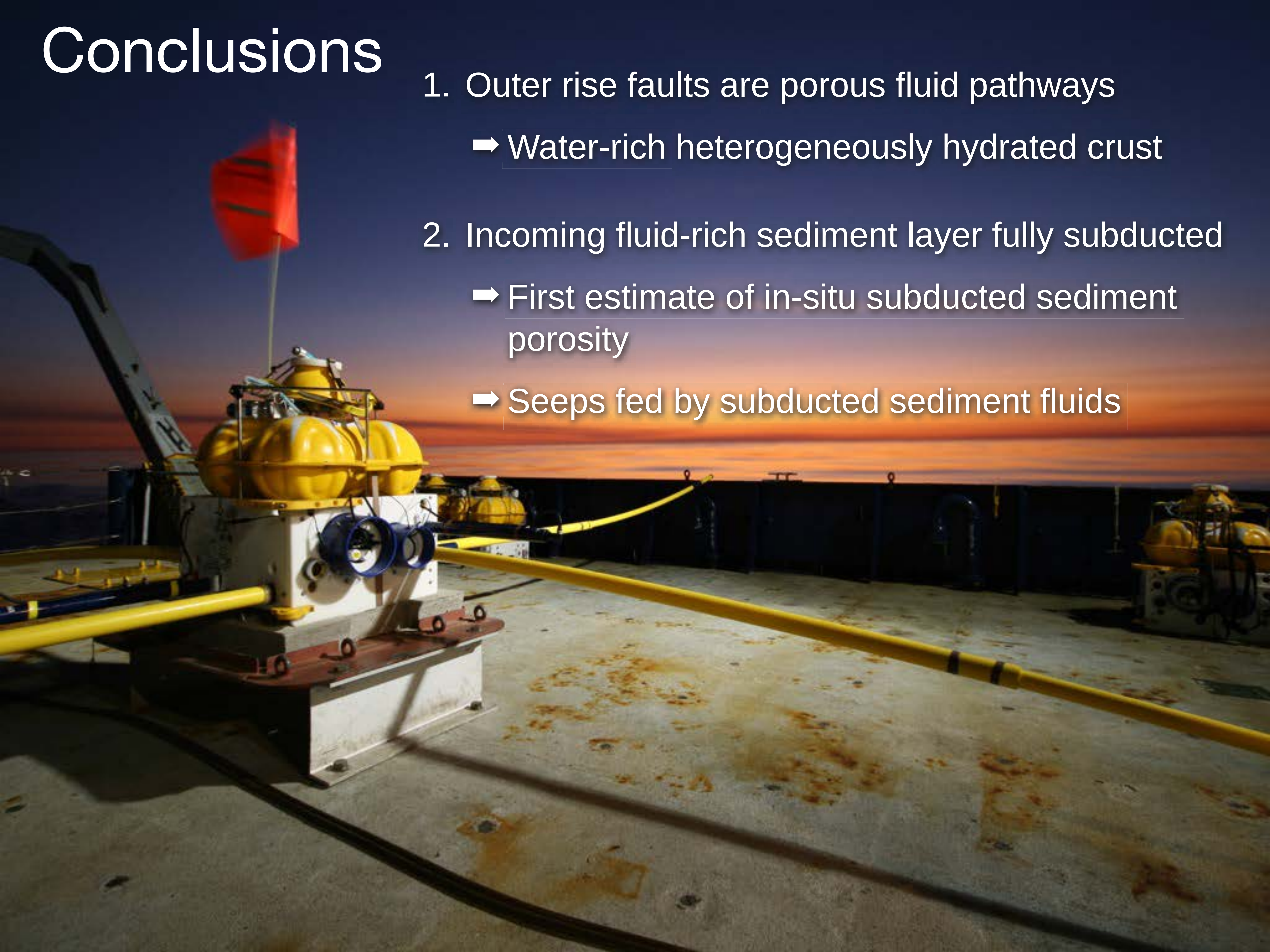
How localized is this feature along axis?


McIntosh et al. (2007)
NICARAGUA
Central America
Map Area
Pacific Ocean
COSTA RICA
Nicoya Peninsula
Contour interval 500 meters


Resistivity (Ωm)
10^0
10^1
10^2
10^3
Depth (km)
0
1
2
3
4
5
6
7
8
9
0
5
10
15
20
25
30
35
Distance from trench (km)


SW
NE
10 km
VE =1.5
NIC 50
Depth Section
CMP Number
Sandino basin
rotated blocks
SM
plate boundary
seismogenic zone
Depth (km)

Conclusions



1. Outer rise faults are porous fluid pathways
   - ➡ Water-rich heterogeneously hydrated crust
2. Incoming fluid-rich sediment layer fully subducted
   - ➡ First estimate of in-situ subducted sediment porosity
   - ➡ Seeps fed by subducted sediment fluids