A seismic refraction study of the Cocos plate offshore Nicaragua and Costa Rica

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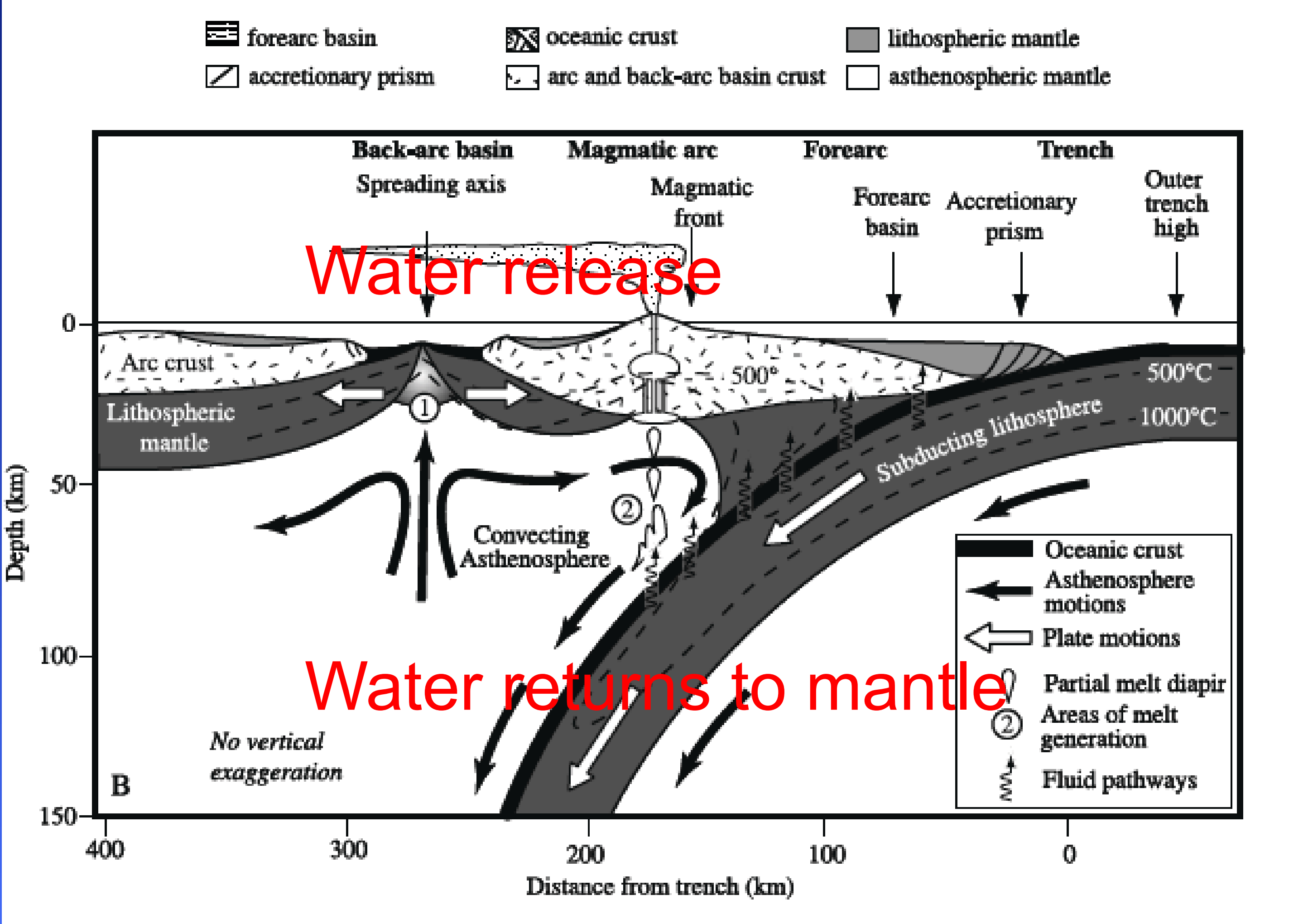
GeoPRISMS
Geodynamic Processes at Rifting and Subducting Margins

MARGINS

NSF

Plate tectonics:

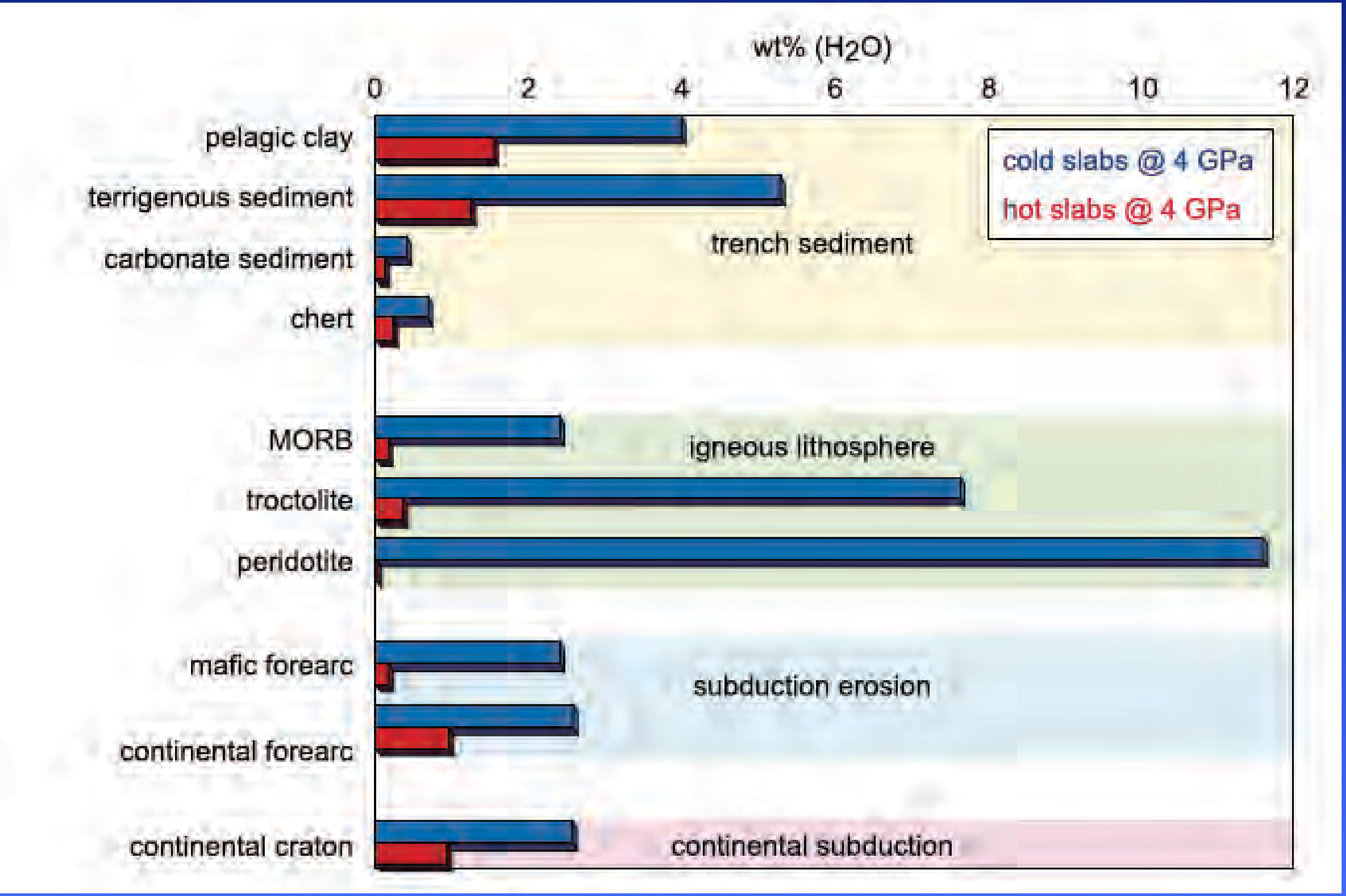
- Large fluxes of solids and volatiles between crust and mantle



Stern (RG, 2002)

Distribution of H_2O in subducting slabs

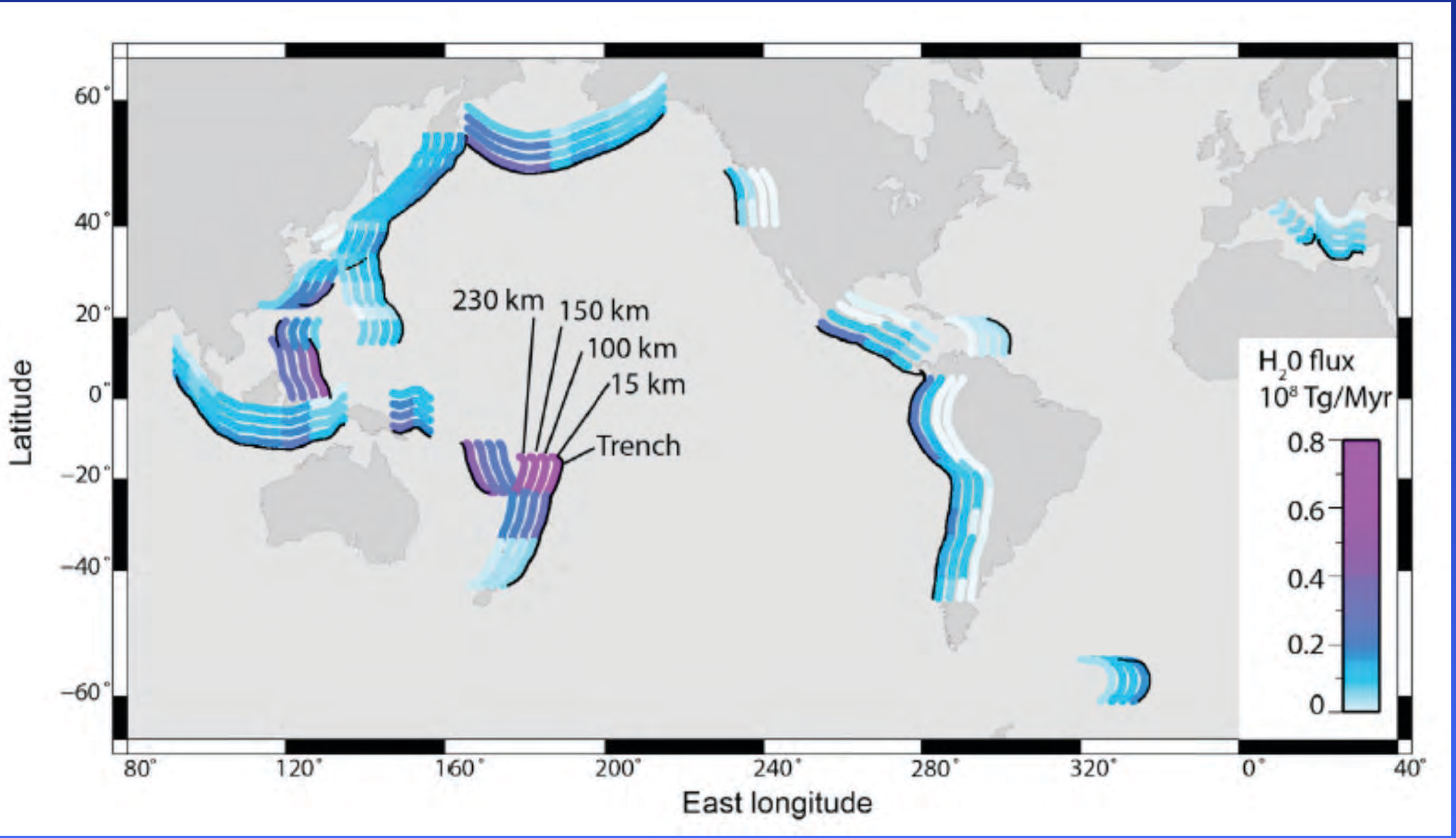
- Mostly in older, colder slabs
- Mantle peridotite can bond with more H_2O



Hacker (GCubed, 2008)

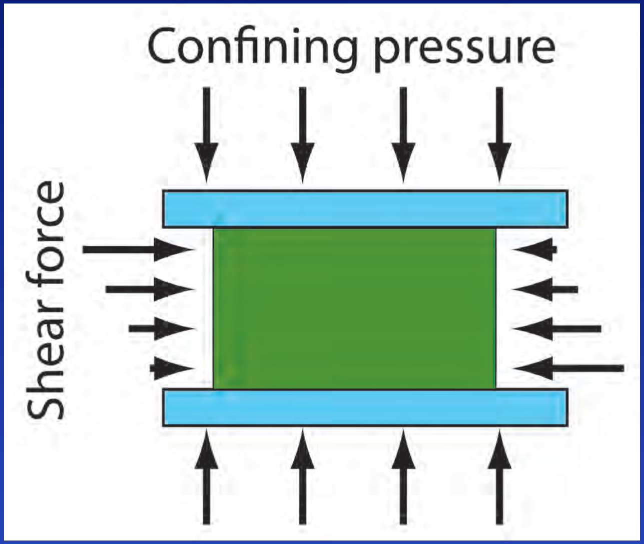
Estimates of water flux in subduction zones

- Based on plate age, convergence speed
- Ignores feedbacks between volatiles, solid earth



Van Keken (JGR, 2011)

Role of water in mantle dynamics



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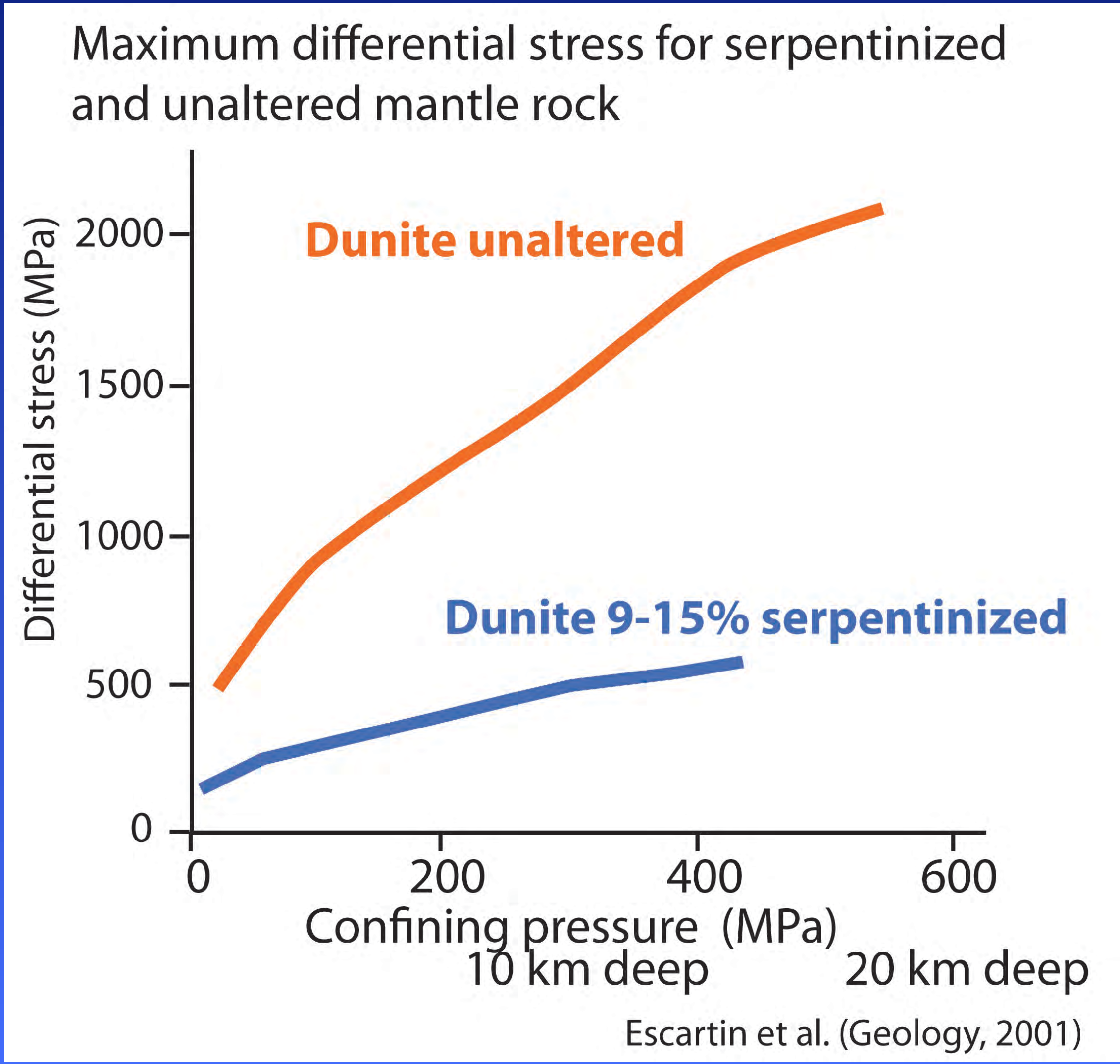
- Dunite is more difficult to break than serpentinite



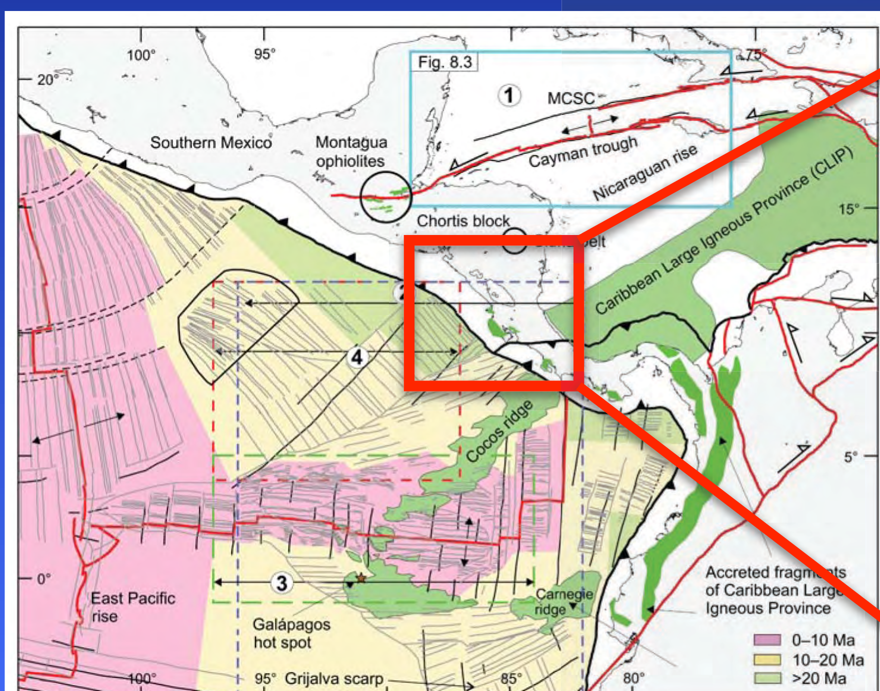
Geodynamic Processes at Rifting and Subducting Margins

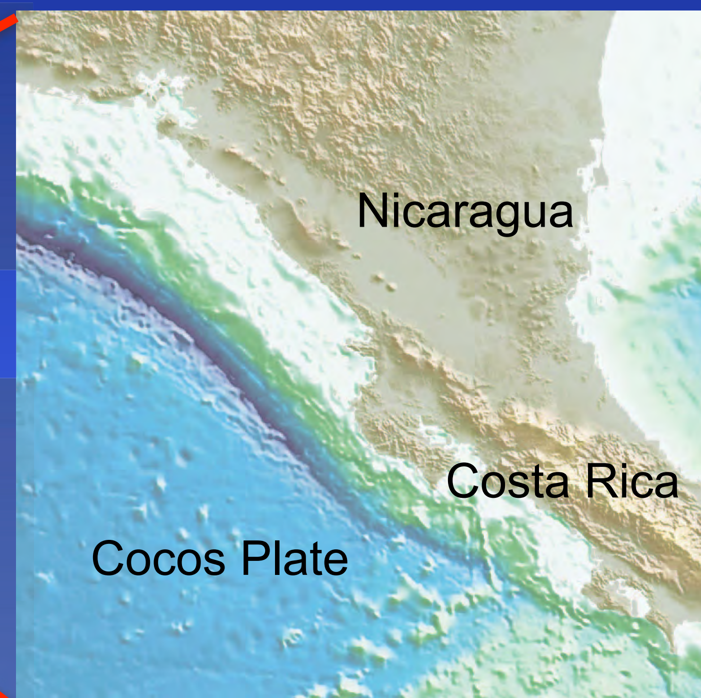
Outline:

- Costa Rica, Nicaragua, and the Cocos plate
- Evidence for larger H_2O flux beneath Nicaragua
- Plate bending and serpentinization
- Galapagos hotspot
- OBS seismic refraction data
- Tomography - Seismic velocity model
- Estimated of H_2O content in downgoing slab mantle
- Conclusions

Pacific margin of Central America: A convergent plate boundary

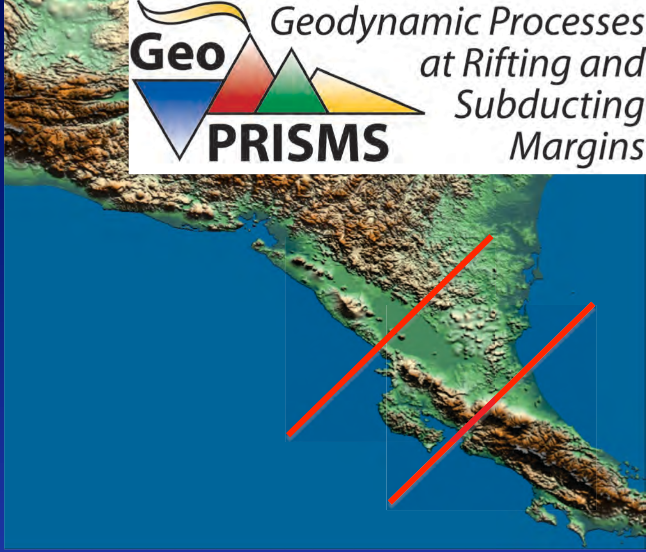
- Along-strike variations
- Contrasts between Nicaragua and Costa Rica





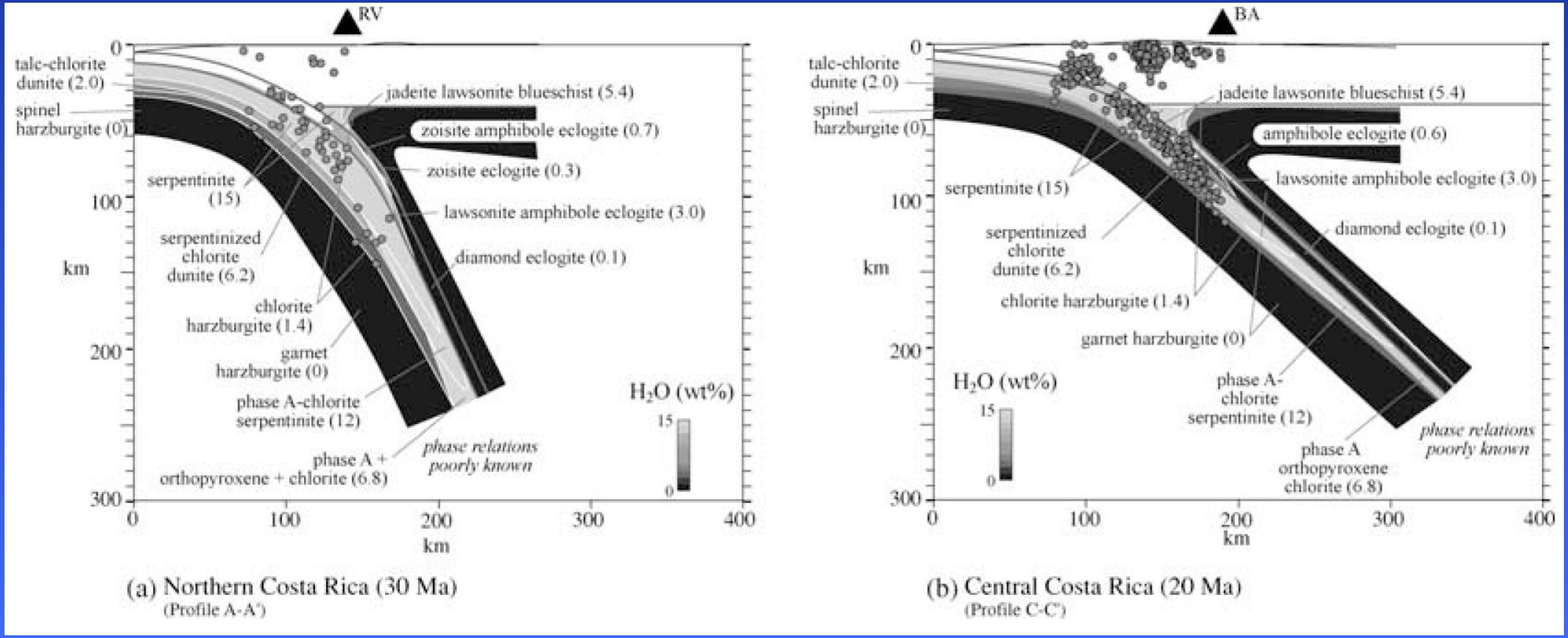
Mann (2007)

Why CR + NIC?



- Strong science community
- The plate boundary is well defined
- Slab dip, seismicity and volcanism in Costa Rica and Nicaragua differ

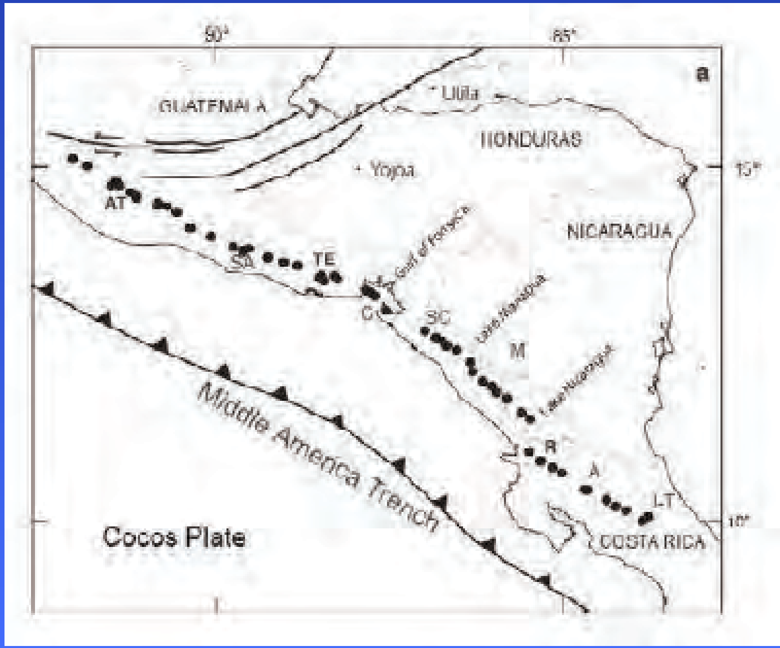
Nicaragua: Steep subduction. Costa Rica: Shallow subduction



Husen et al. (GJI, 2003)

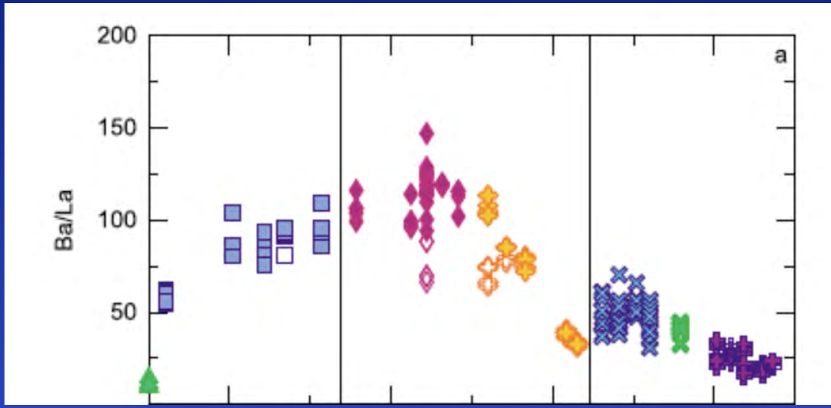
Arc geochemistry and tectonics

- Slab fluids: Soluble / Insoluble elements
- Most common is Ba / La
- Global maximum in Nicaragua, smaller slab influence in Costa Rica
- Correlates with slab dip

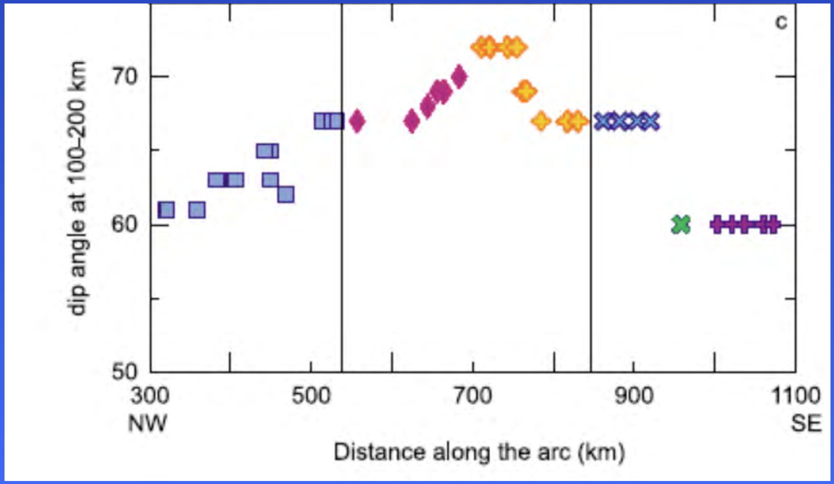


- Ba/La in arc lavas

Guatemala El S. Nicaragua Costa Rica



Slab dip



Bolge et al. (G-Cubed 2009)

Data compilation

Geochemistry
Ba/La (blue) larger in NIC
B/La (red) larger in NIC
^{18}O (yellow) smaller in NIC
^{10}Be (not shown) larger in NIC

Slab dip
Larger in NIC

Cocos plate
Bending / faulting off NIC
Seamounts / ridges off CR

➢Is there a causal relationship between geochemical indicators?

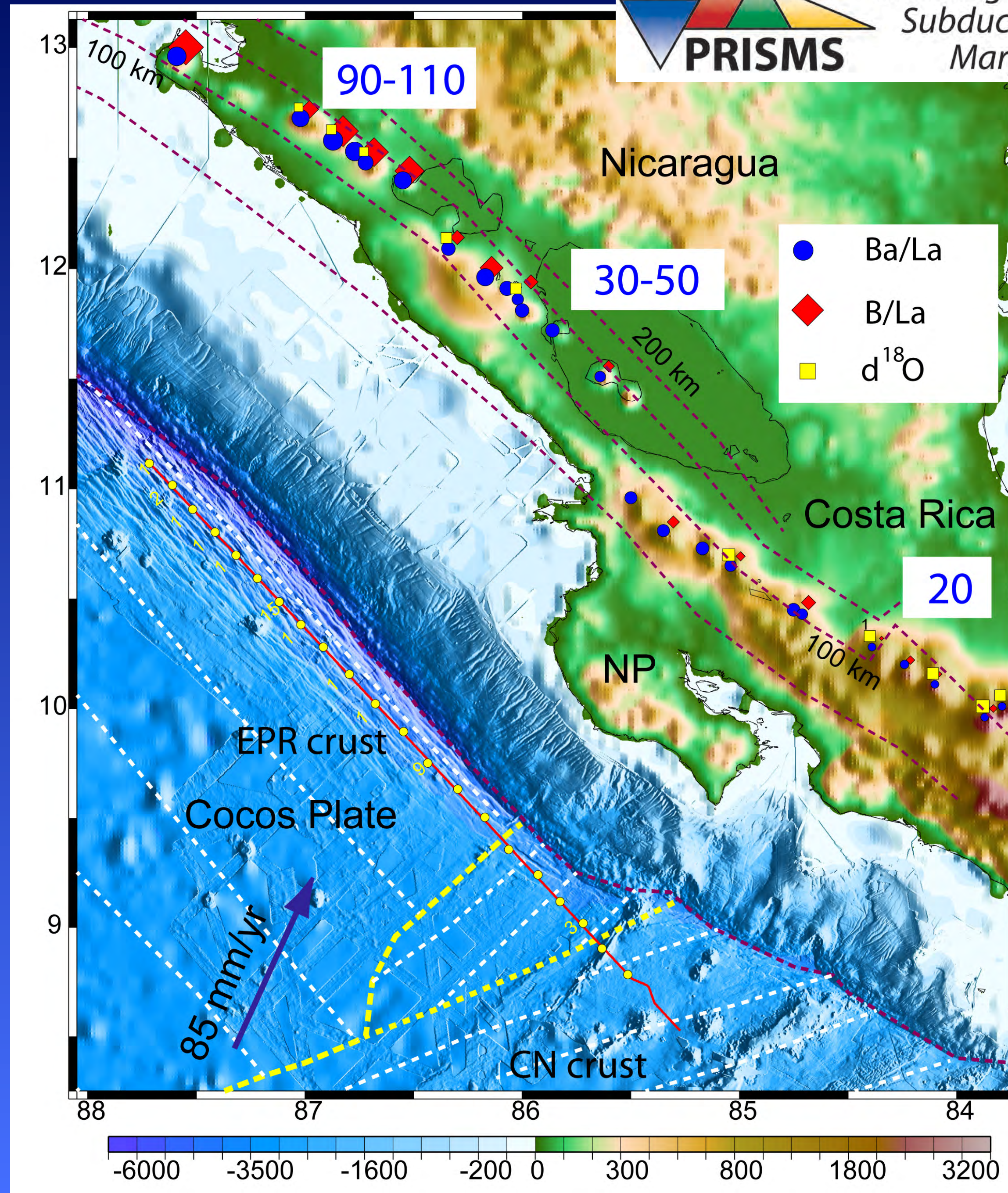


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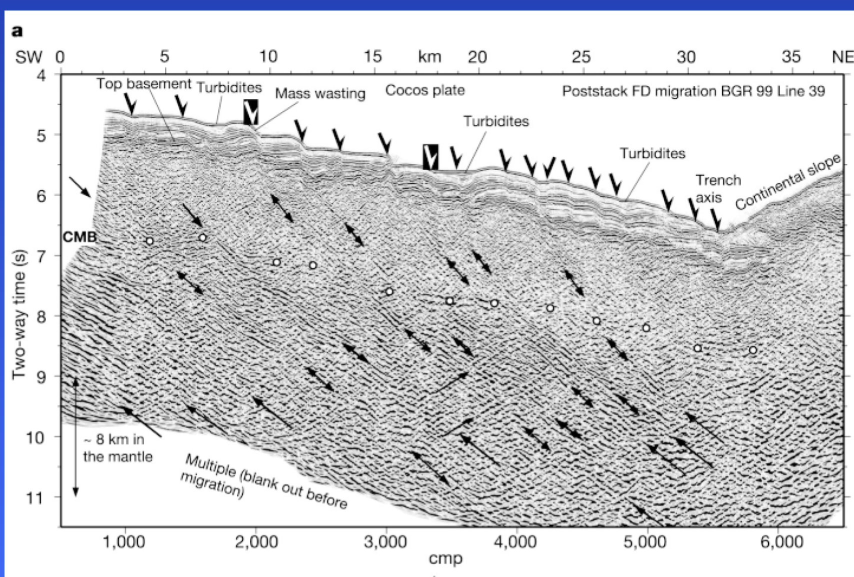
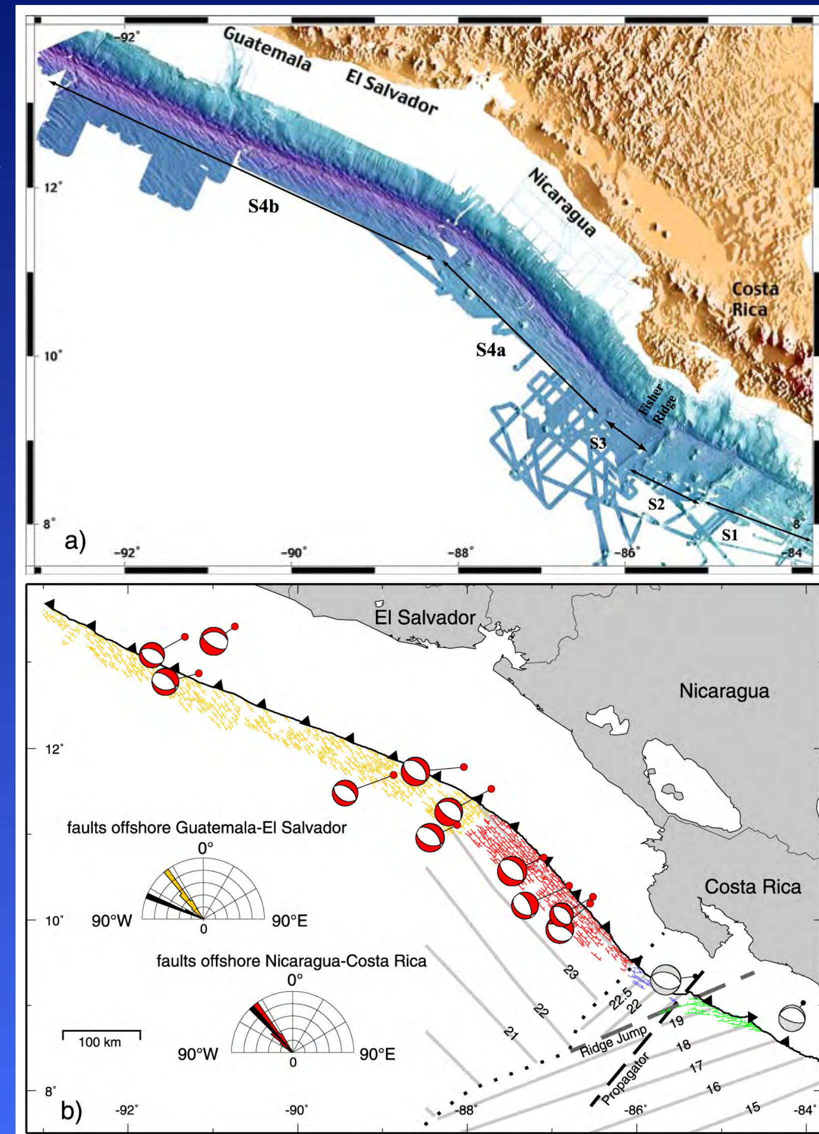
Plate bending and faulting

- Faulting Cocos plate offshore Nicaragua
- Faults penetrate Moho 6 km below seafloor
- Seismically active
- Likely serpentinization of oceanic mantle



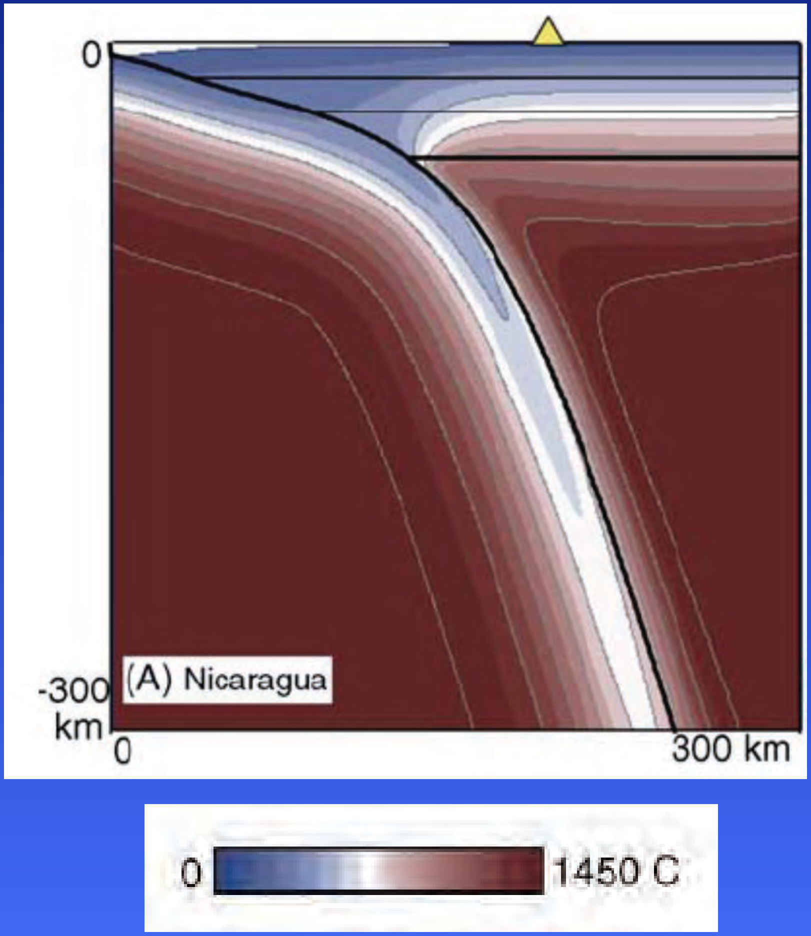
Ranero et al. (Nature, 2003)

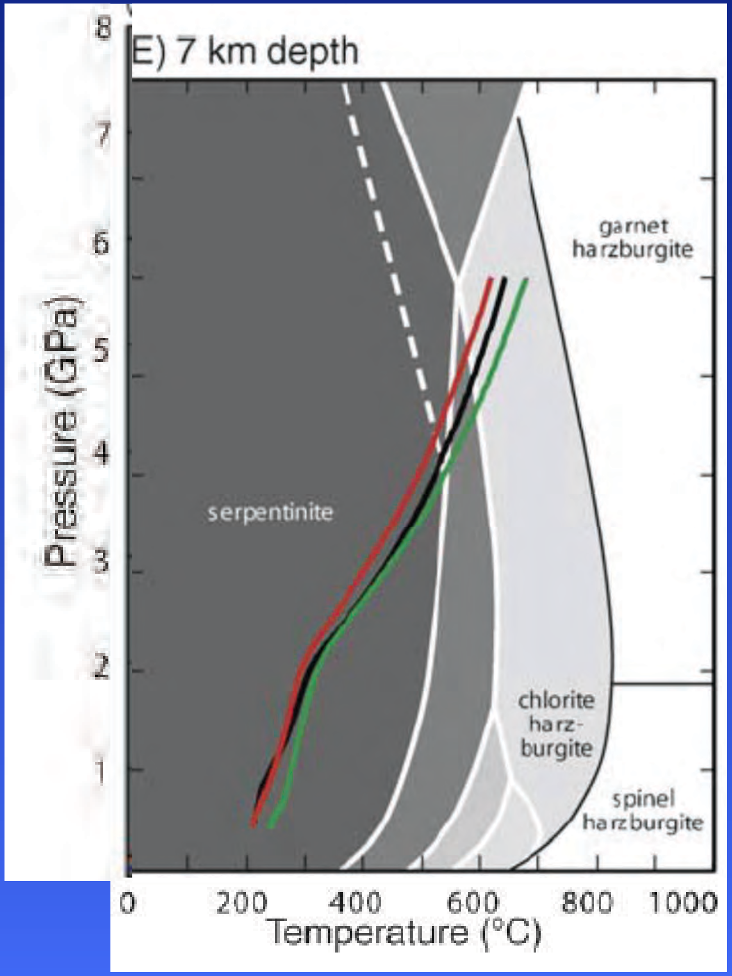


Ranero et al. (G-Cubed, 2005)

Geodynamic model temperature profile

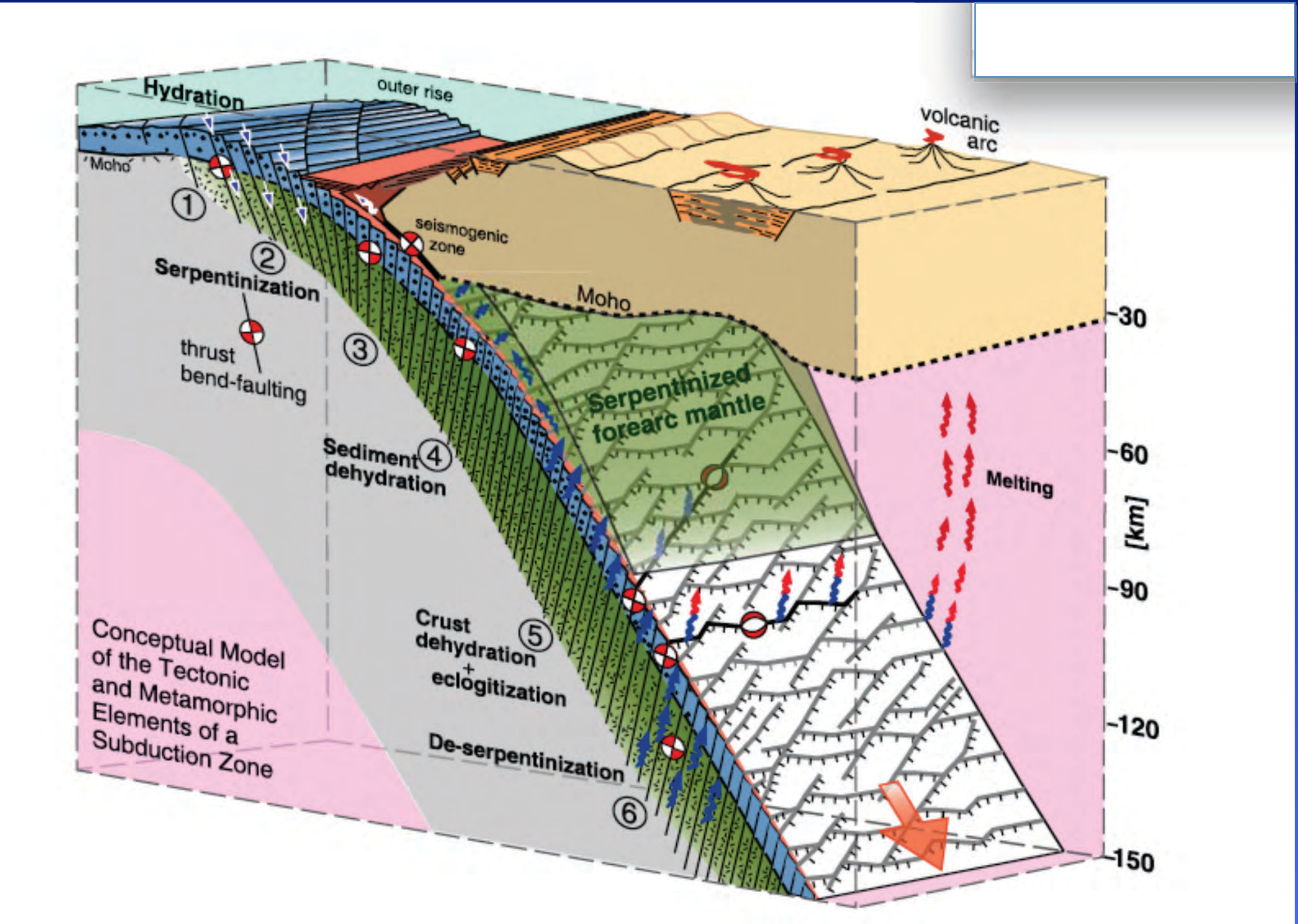
- Helps estimate metamorphic fluid release
- Depends on depth beneath slab surface





Peacock et al. (2005)

Model for hydration and dehydration in the downgoing plate



Ranero et al. (2005)

Wet slab hypothesis:

1. Steep subduction beneath Nicaragua leads to increased bending, faulting of downgoing Cocos plate.

2. Mantle of downgoing plate is serpentinized at the outer rise of the Middle American Trench.

3. Water is released from subducting slab mantle at 100 km depth, where serpentinite breaks down.

4. Water leaches soluble trace elements (such as Ba) from the 400 meter sediment cover on the Cocos plate and infiltrate the mantle wedge.

5. The addition of water lowers the mantle wedge melting temperature, and hydrous melts rise to the arc.

6. Arc lavas have elevated Ba/La and B/La.

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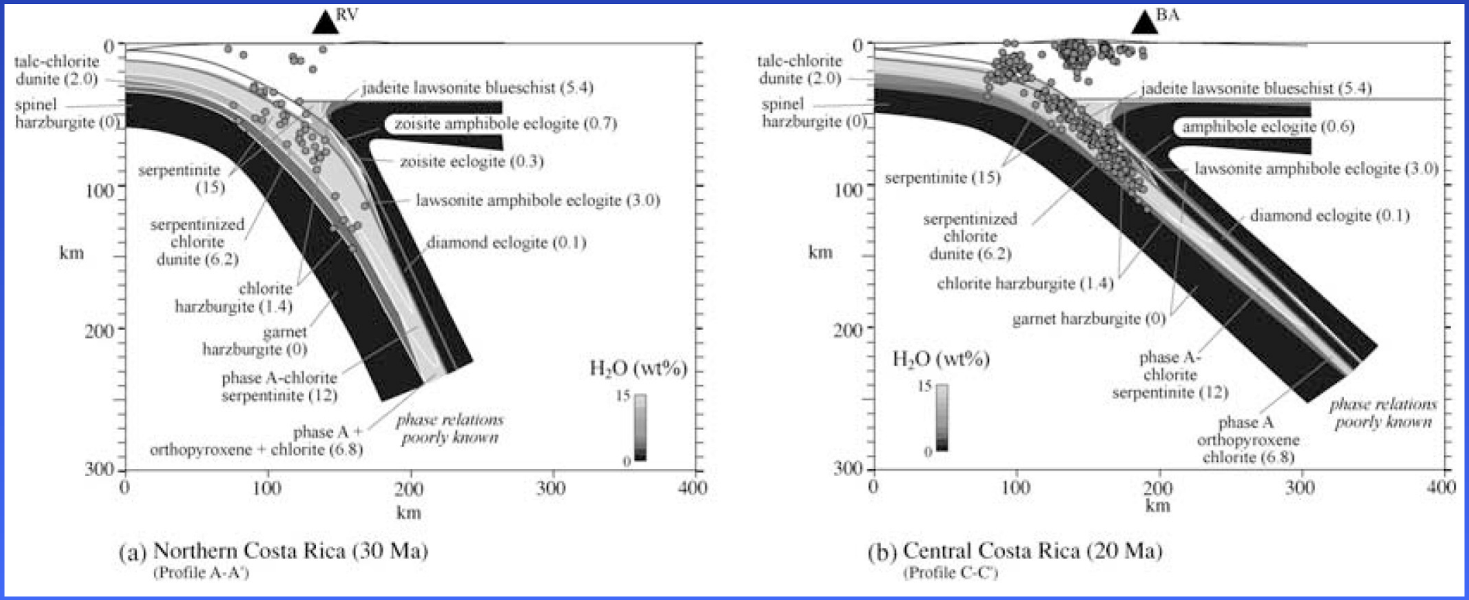
Steeper slab = larger, or more focused flux of H_2O?

- The broadband seismic results give compelling evidence for a plume of hydrous fluids or melts , but……
- Instead of a larger flow of H2O, the larger plume beneath Nicaragua could be caused by a more concentrated plume. Simply because the slab beneath Nicaragua is steeper, H2O will be released in a narrow column. (Carr et al., GCubed 2007).

NIC CR



Husen et al., (GJI, 2003)

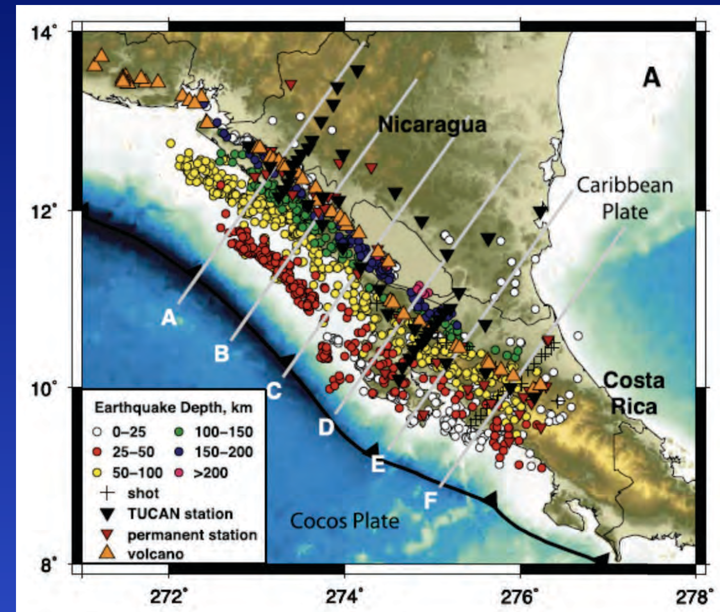
Broadband seismic imaging

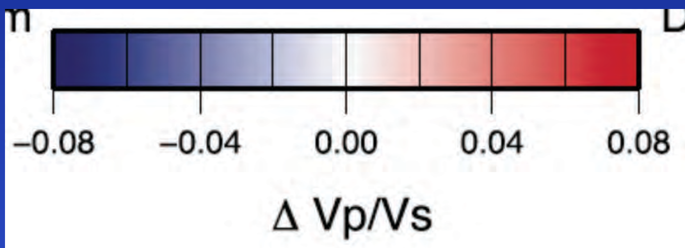
TUCAN experiment

Low Vp/Vs indicates presence of fluids

More melt/water beneath Nicaragua

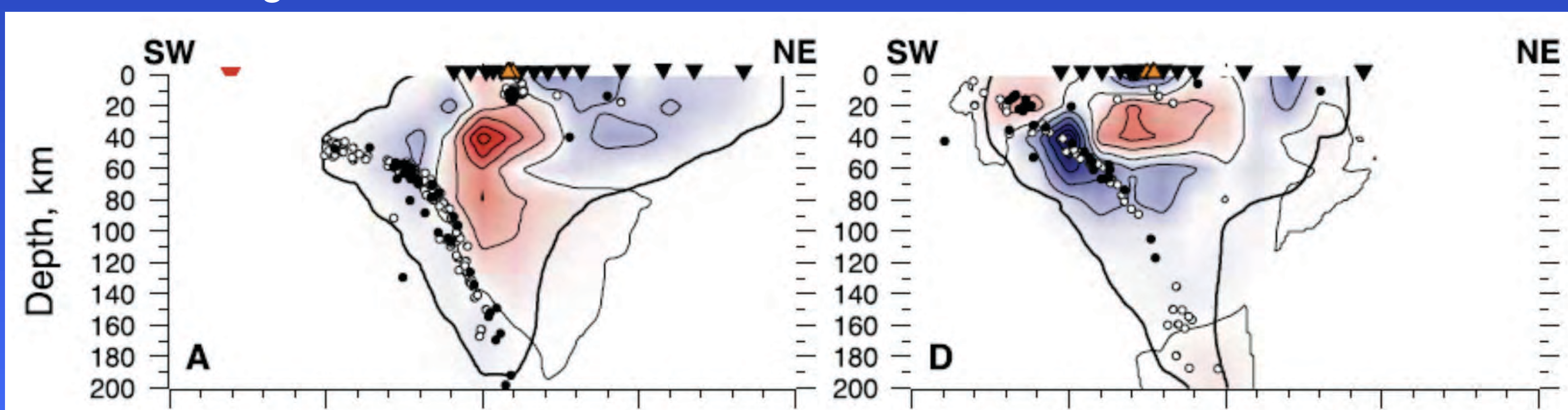
Water induces melting mantle wedge





Nicaragua

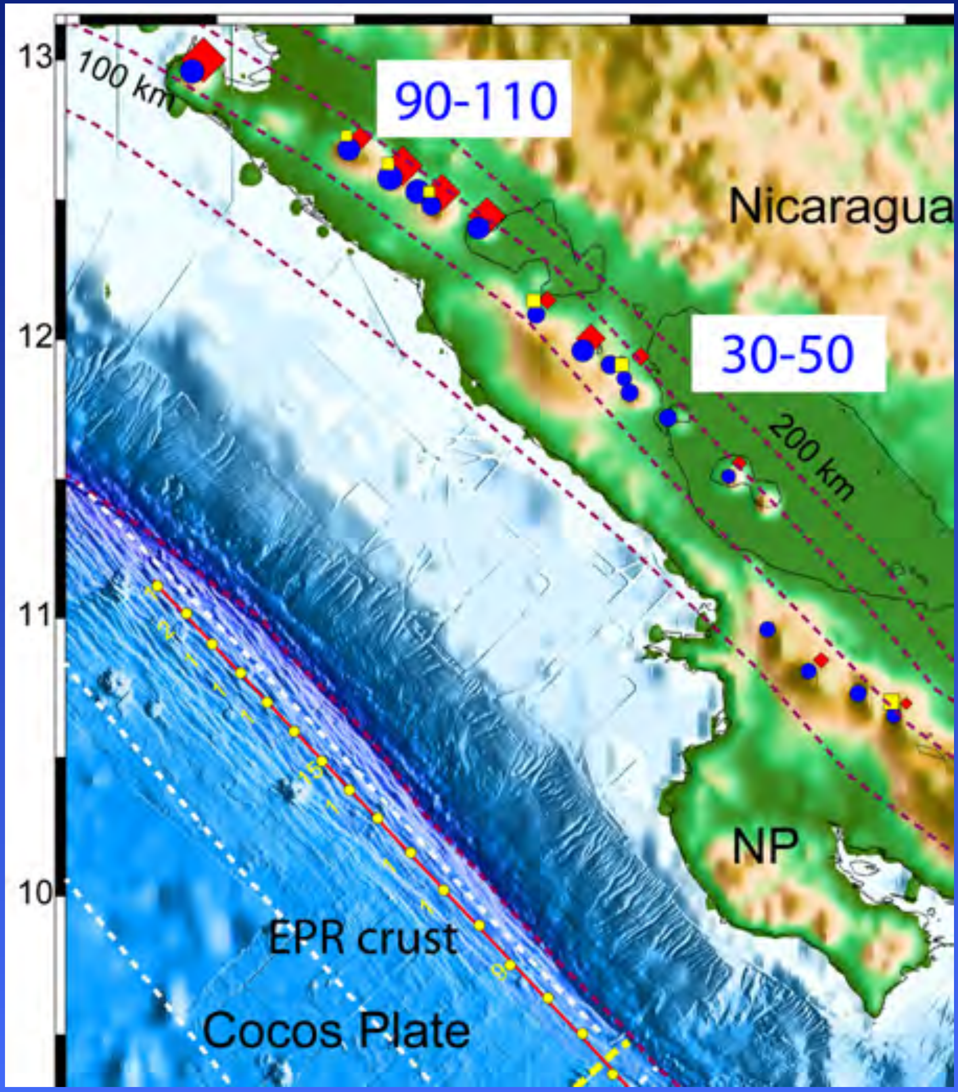
Costa Rica



Syracuse et al. (G-Cubed, 2008)

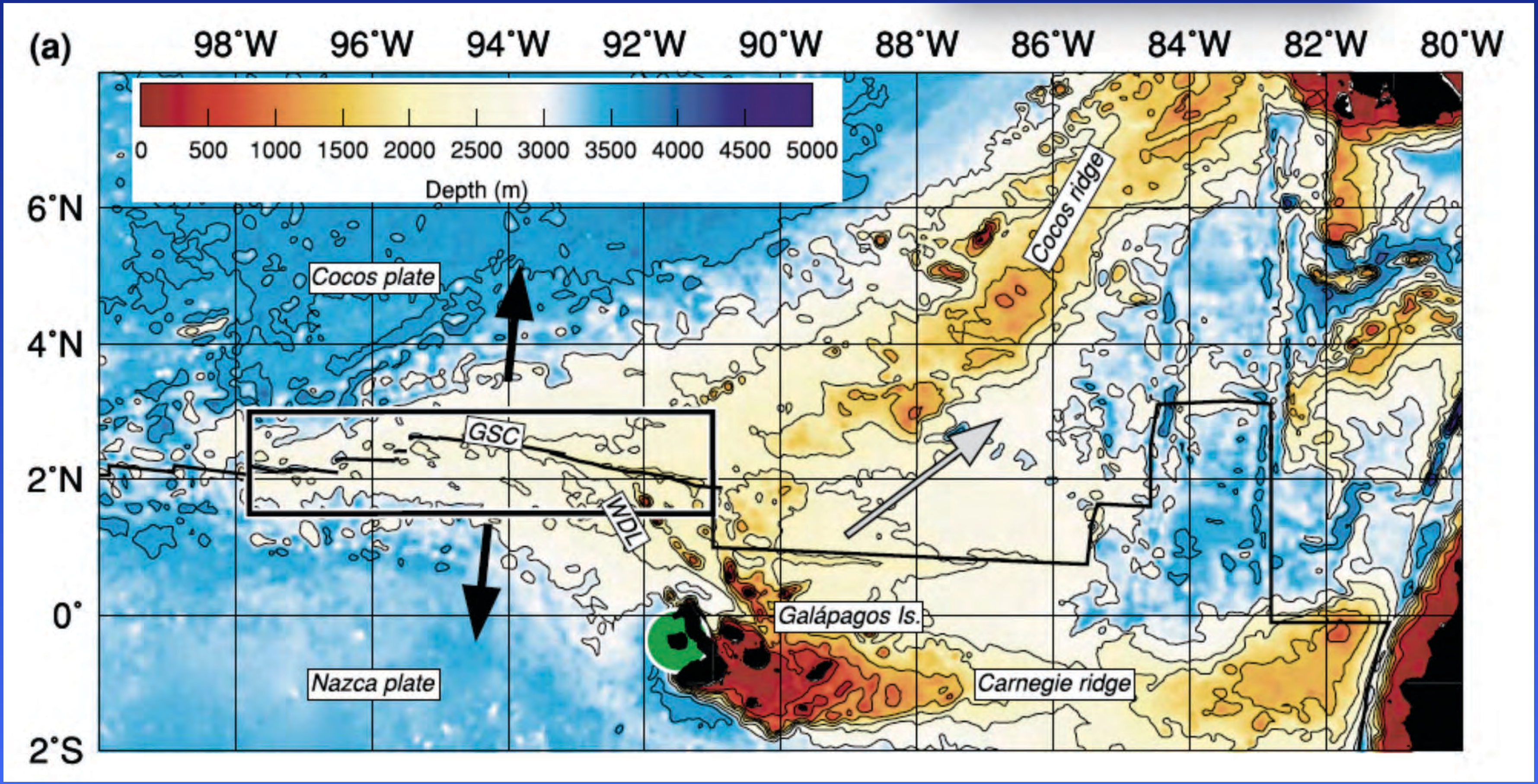
In Nicaragua, Ba/La data may be explained by H2O flux from mantle

- Broadband seismic data provide evidence that high Ba/La values in Nicaragua are indeed the result of faulting and hydration of the Cocos Plate



Galapagos Hotspot

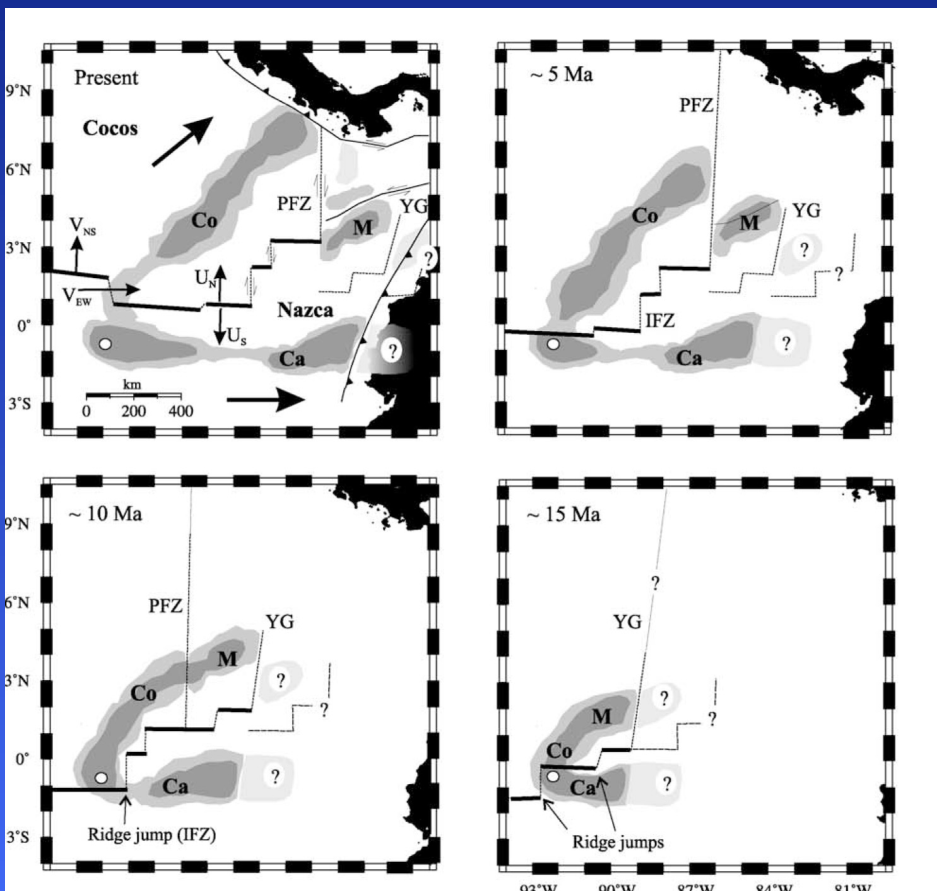
➢Hotspot leaves trace of thick, chemically enriched crust (Cocos Ridge) on Cocos Plate



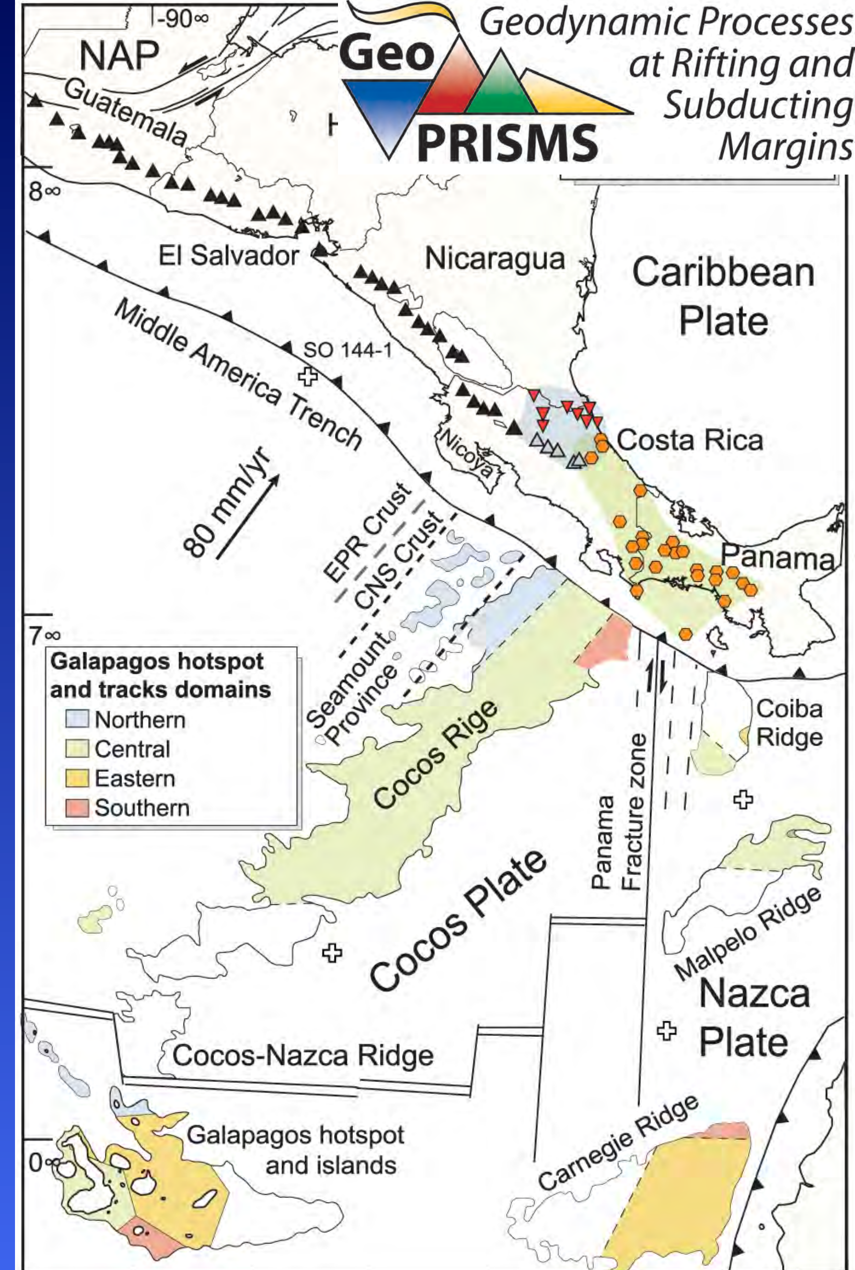
Canales et al. (2004)

Cocos Ridge

- ➢Galapagos hotspot was never far from C-N spreading center
- ➢Plateau with 20-km-thick plateau



Sallares and Charvis (EPSL 2003)

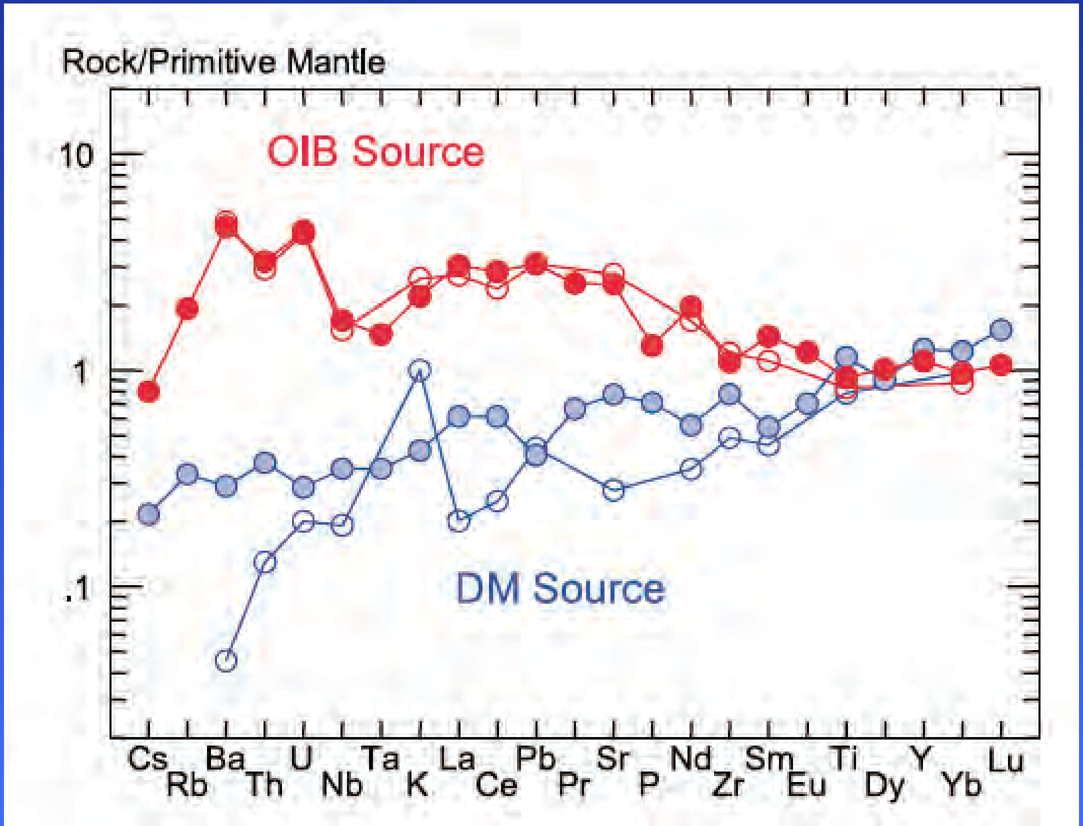


Gazel et al. (G-Cubed 2008)

Alternative hypothesis:

- Large Ba/La and B/La in Nicaragua is largely due to OIB enriched source in Costa Rica

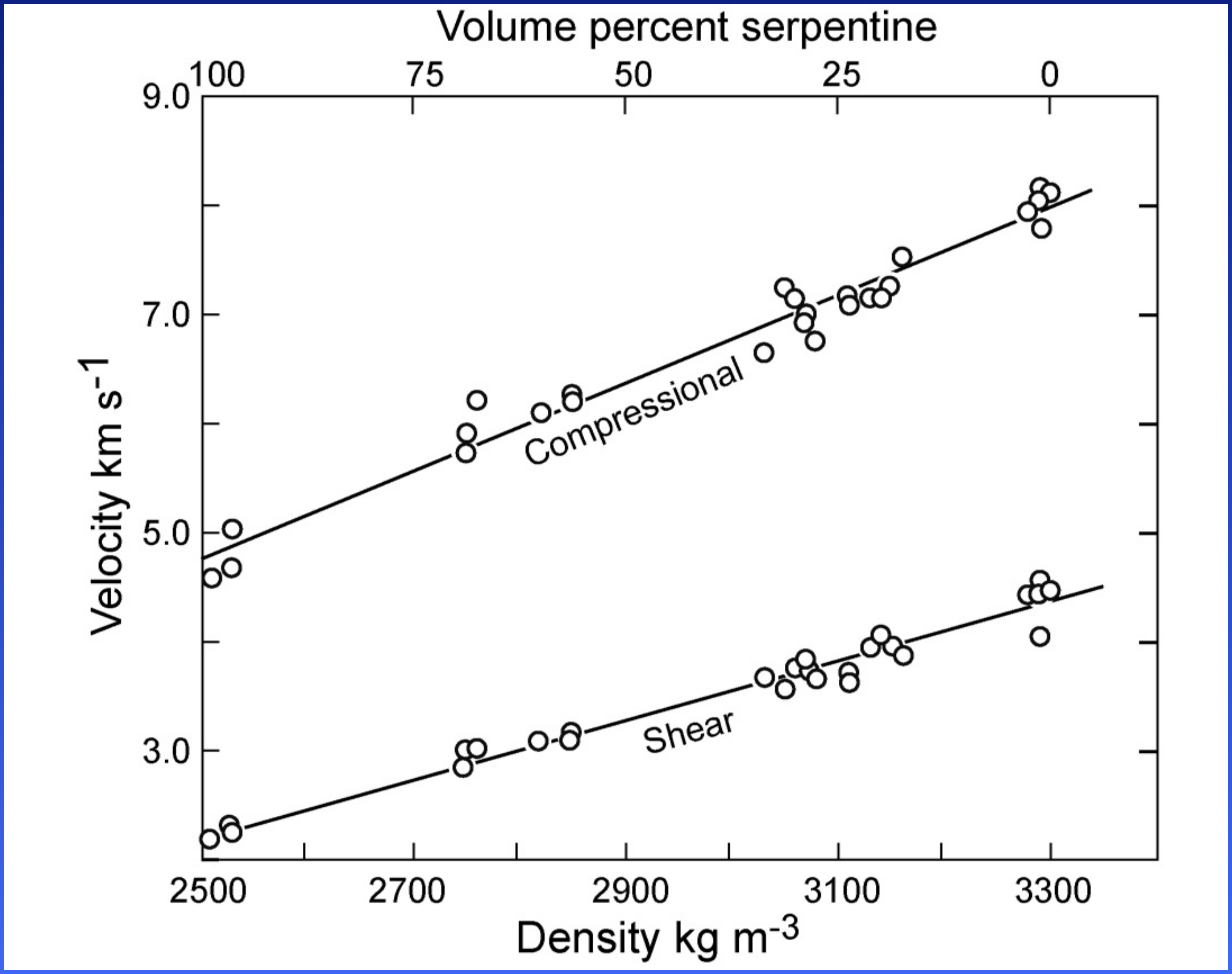
- Galapagos hotspot enriched crust offshore central Costa Rica
- Large La concentrations where Cocos Ridge crust subducts



Direct measurements of H20 in mantle from seismology

- Seismic refraction studies of Middle American Trench
- Ocean-bottom seismometers record surface shots from seismic ship
- Tomography imaging oceanic crust and mantle
- Lower seismic wave speeds in mantle
- Faulting, presence of fluids, serpentinization

Serpentinization vs seismic velocity



Christensen, (IGR 2004)

Existing and new seismic refraction data along MAT

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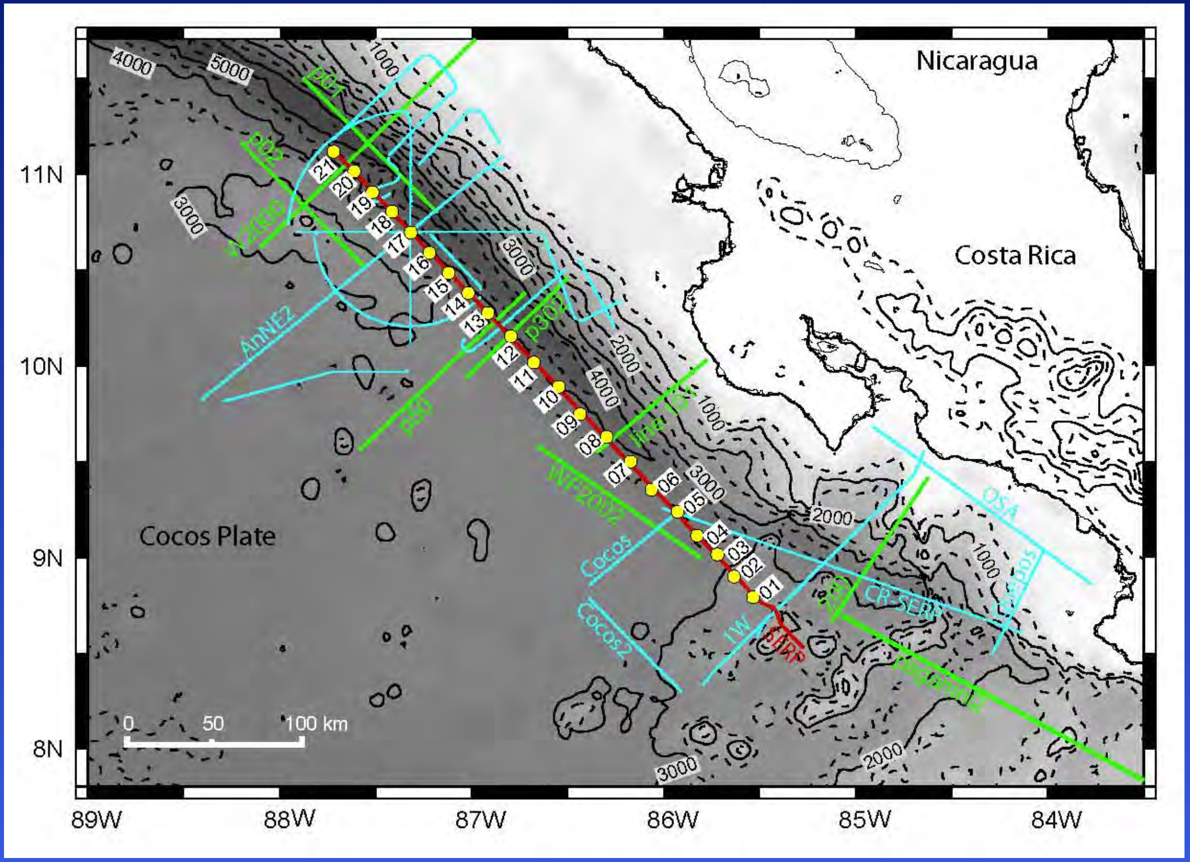
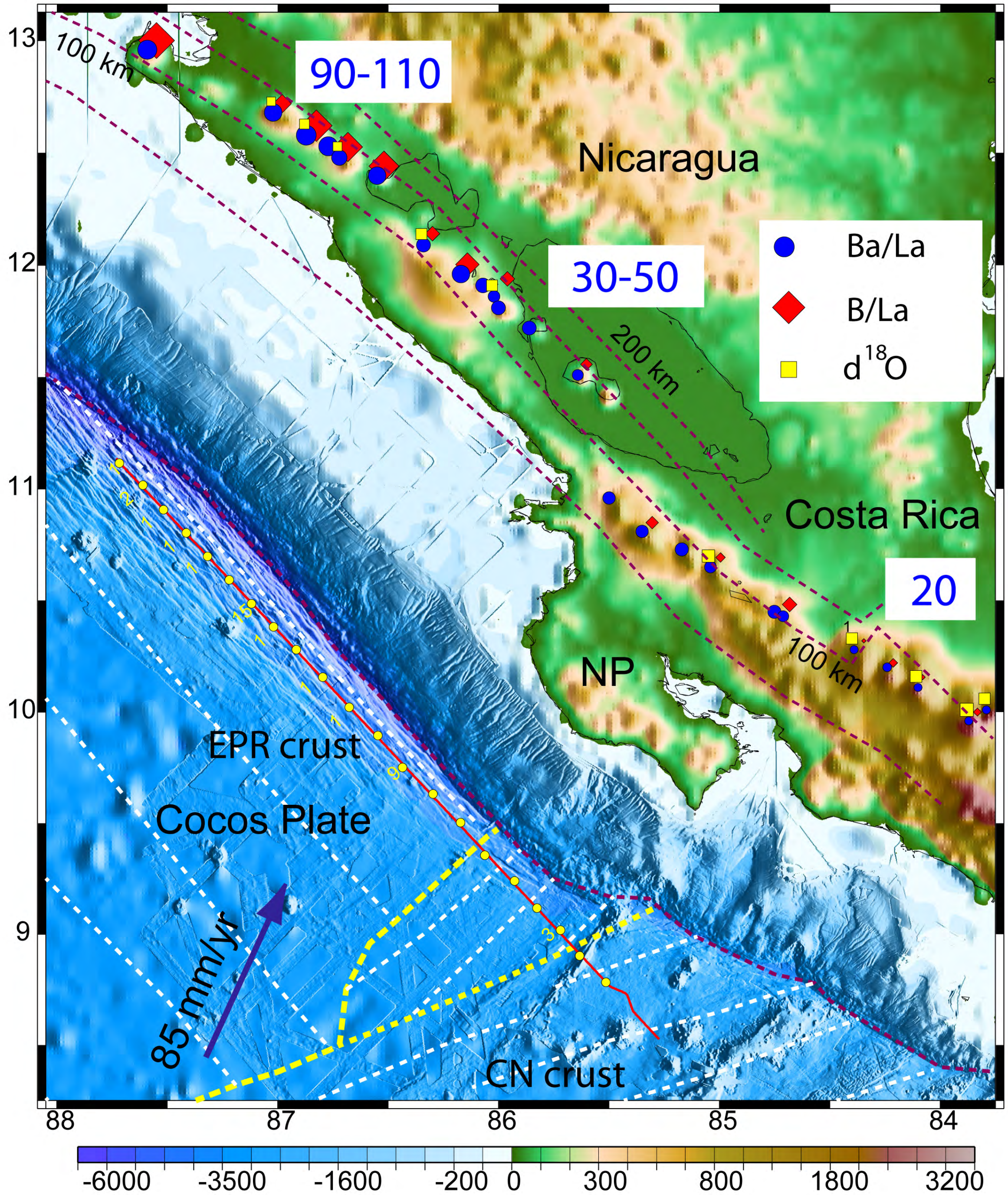


➢Green lines, previous studies (UTIG, GEOMAR)

➢Blue lines, also gathered in 2008

➢SERP (red) is unique for its length and orientation



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Line SERP

- Spring 2008
- 396 km, trench parallel
- EPR and CN ocean crust
- R/V Marcus Langseth
- 21 Ocean-bottom seismometers
- 2-minute shot spacing
- Aiming for deep mantle arrivals

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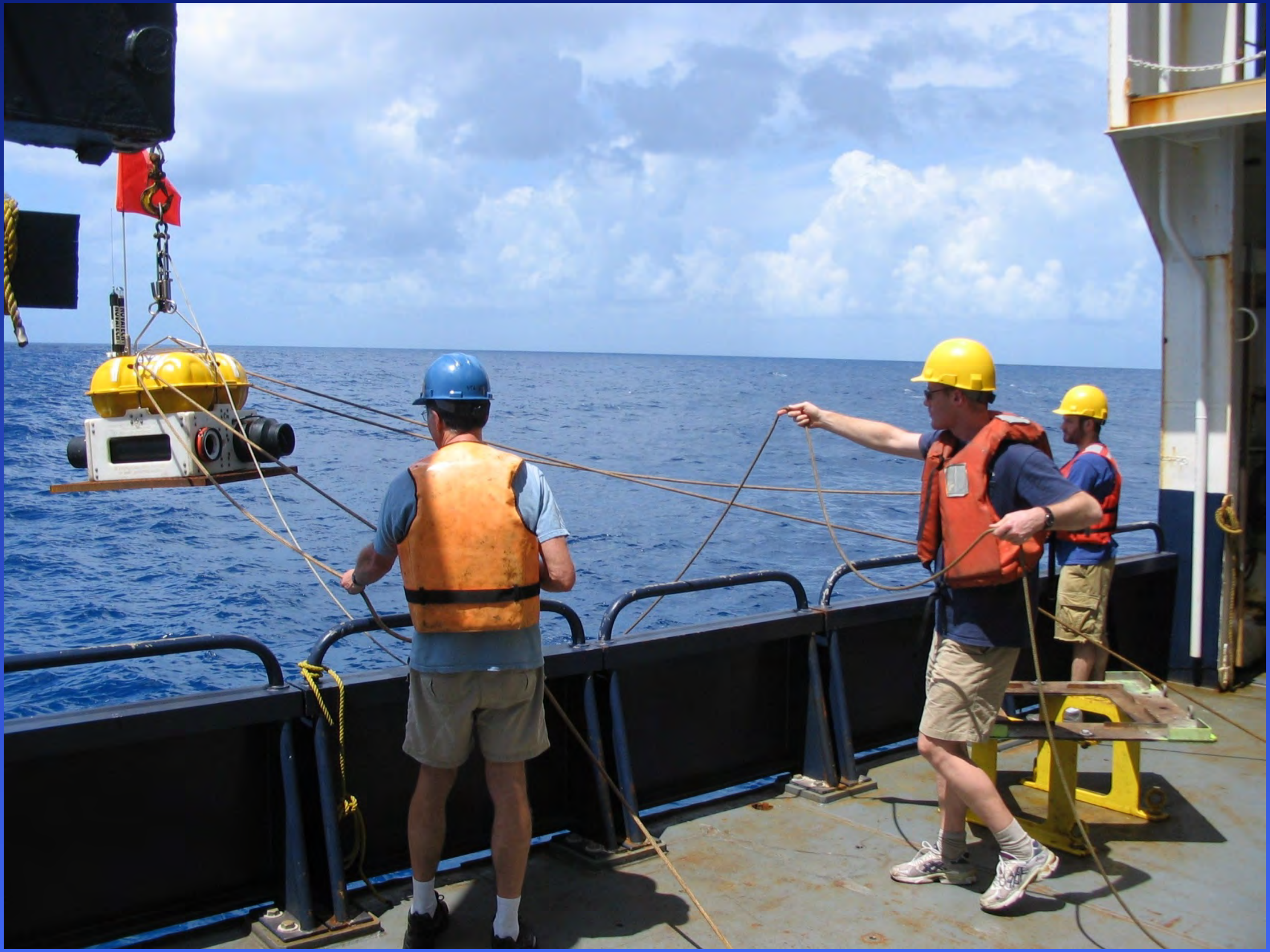
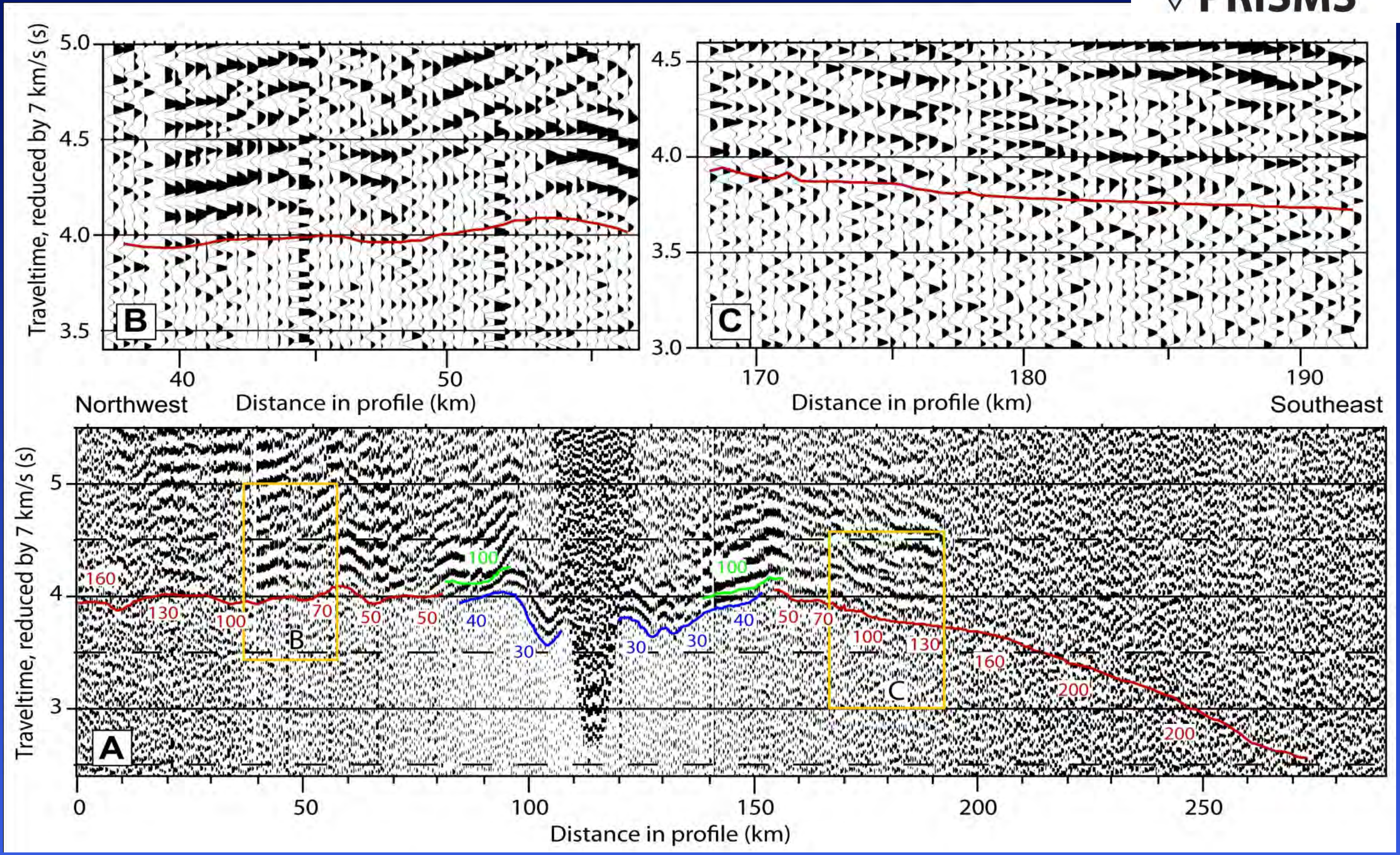
Deployment of Scripps OBS



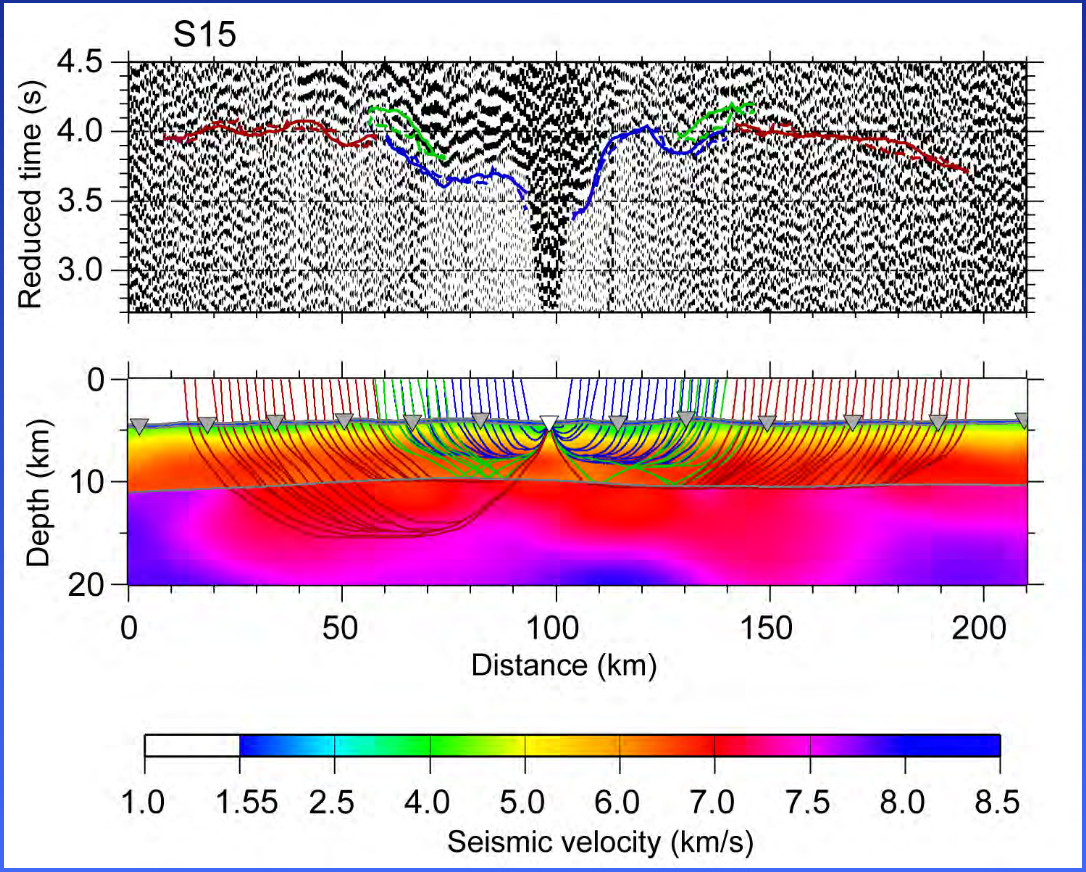
Ocean-bottom seismometer record



- Crustal refractions (Pg), Moho reflections (PmP), mantle refractions (Pn)
- Travel-time pick uncertainty increases with source-receiver offset
- Maximum offsets to about 150 km

Data fit of OBS 15, EPR crust

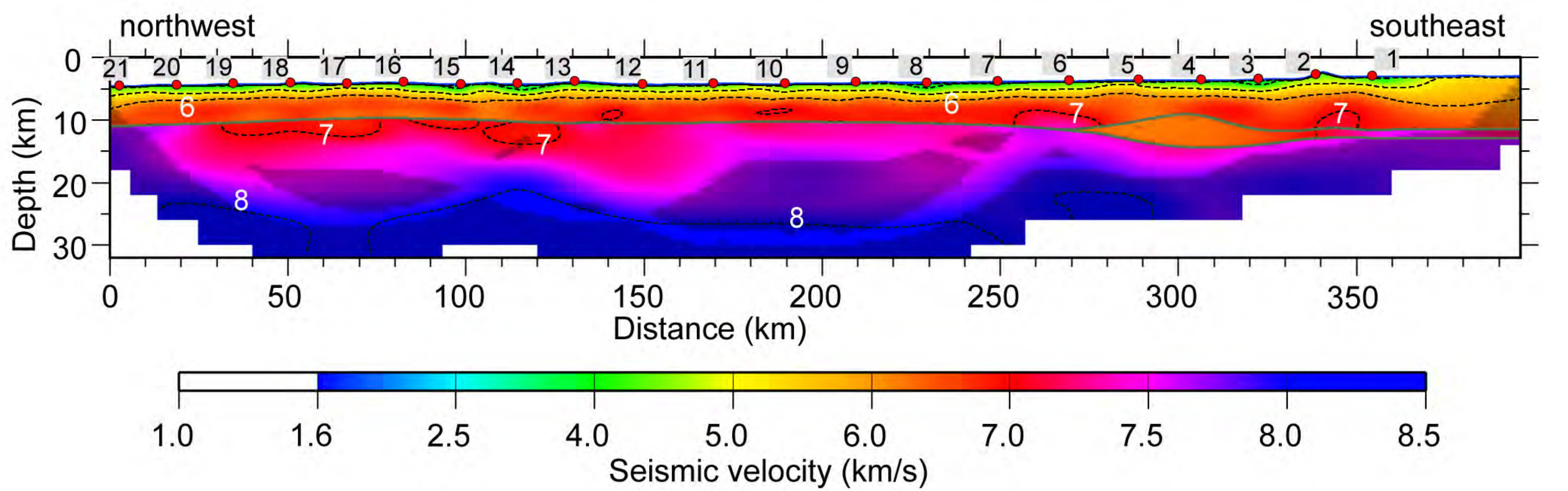
- Traveltime axis reduced by 7 km/s
- Solid curves picked, dashed curves caluclated traveltimes
- Normal record for fast-spreading crust, except for low mantle seismic velocities



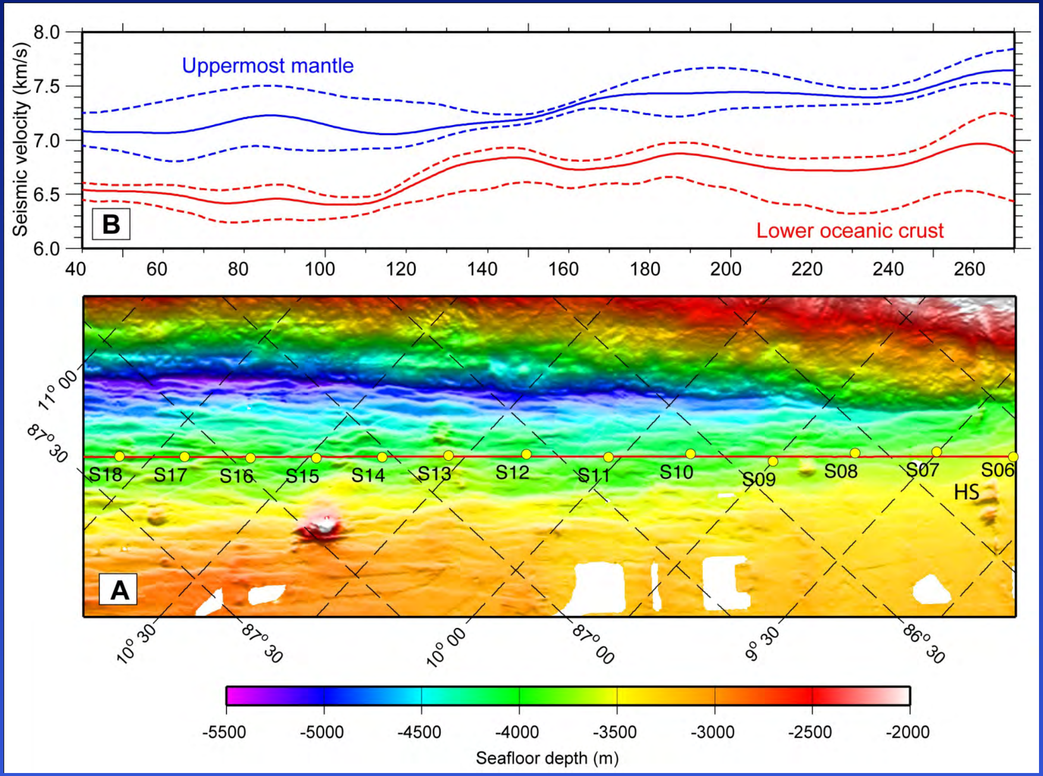
Van Avendonk et al. (GCubed, 2011)

Reflection/refraction tomography

- Layered model with Moho, underplating
- Thick (10 km), crust at CN segment
- Normal thickness (6 km) crust EPR segment
- Serpentinization increases with faulting of seafloor
- Serpentinization to 6-10 km beneath Moho



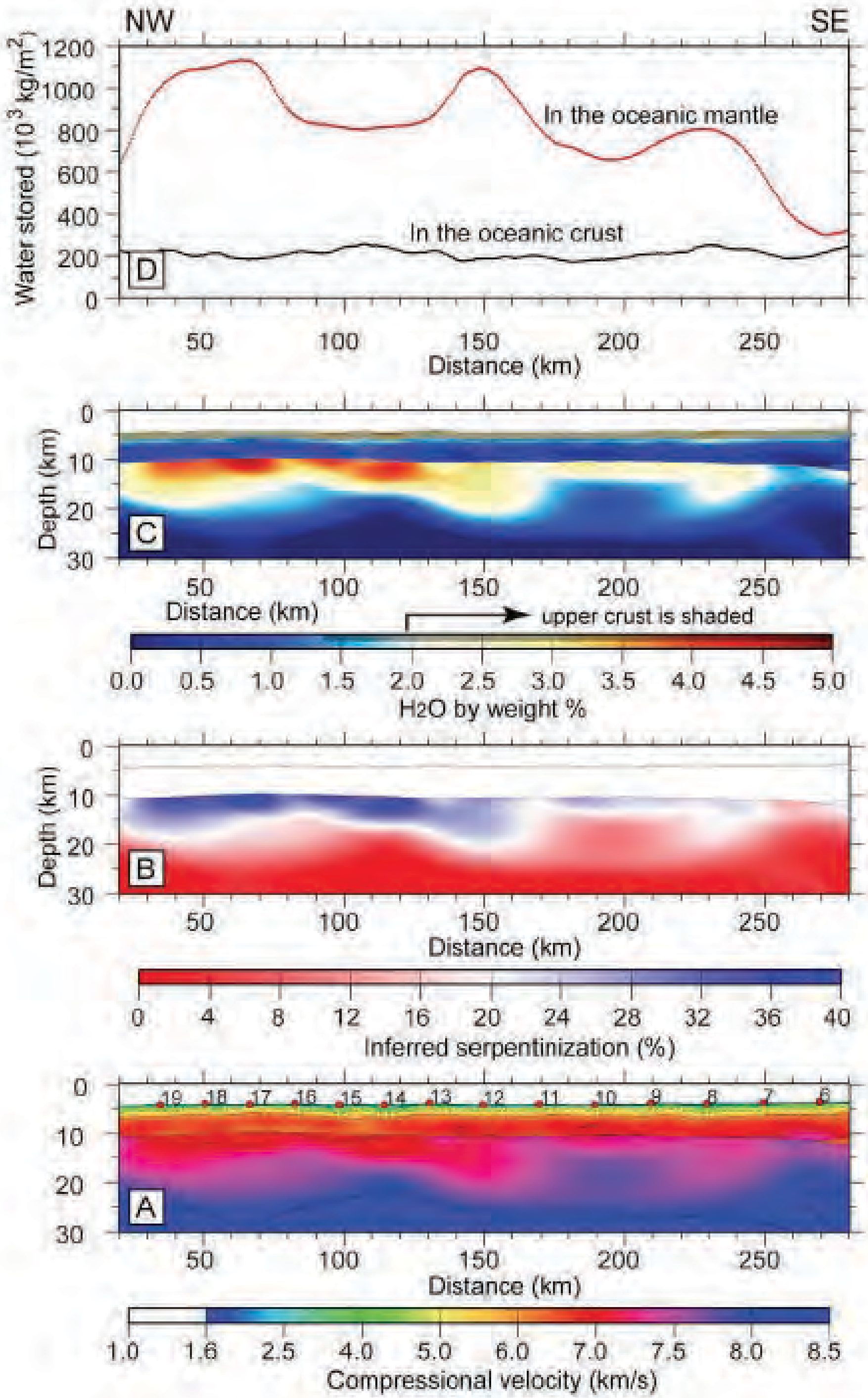
Van Avendonk et al. (GCubed, 2011)



Van Avendonk et al. (GCubed, 2011)

Plate faulting and serpentinization

- Both mantle and crustal seismic velocities decrease with faulting near MAT
- Crustal anomaly must be fracturing, free water content
- Mantle seismic velocity could represent 25% serpentinization

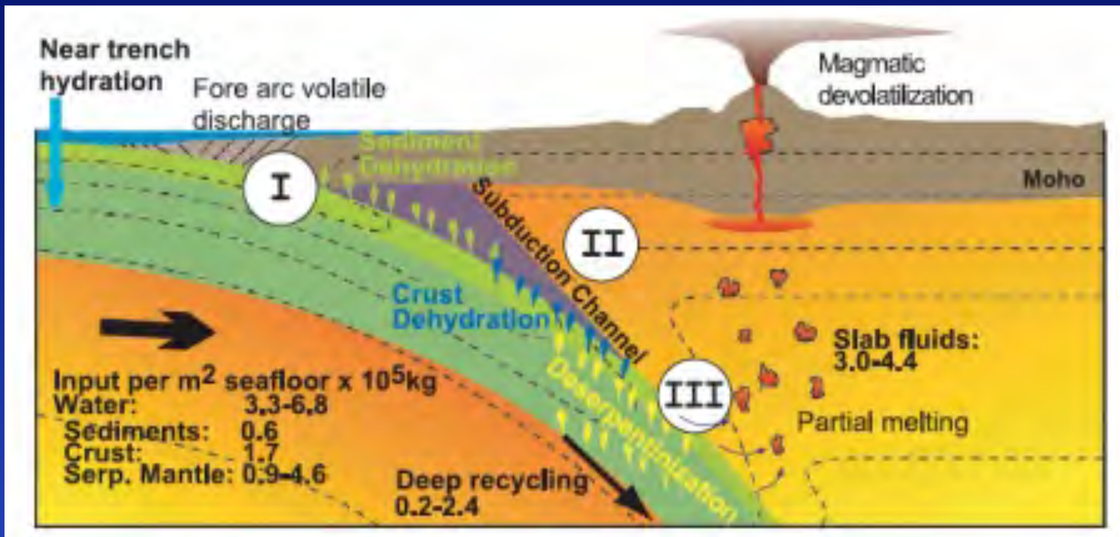


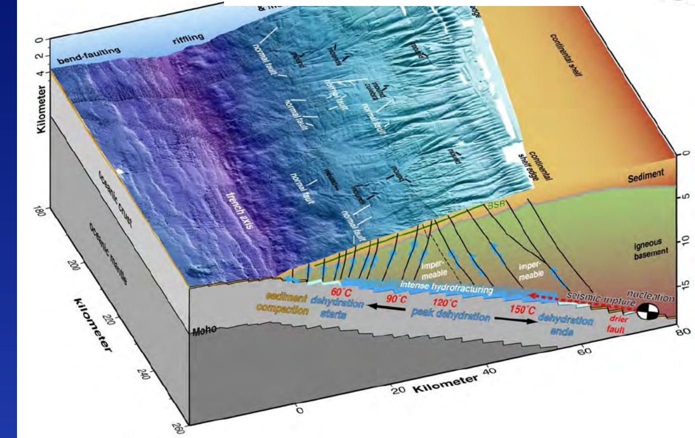
Estimates of H_2O from seismic velocities

- Use empirical relationships to estimate degree of serpentinization, weight percentage of H_2O.
- Oceanic crust does not show variations in water concentration along MAT.
- Mantle of Cocos plate offshore Nicaragua may have 2.5 times more water than offshore Costa Rica.

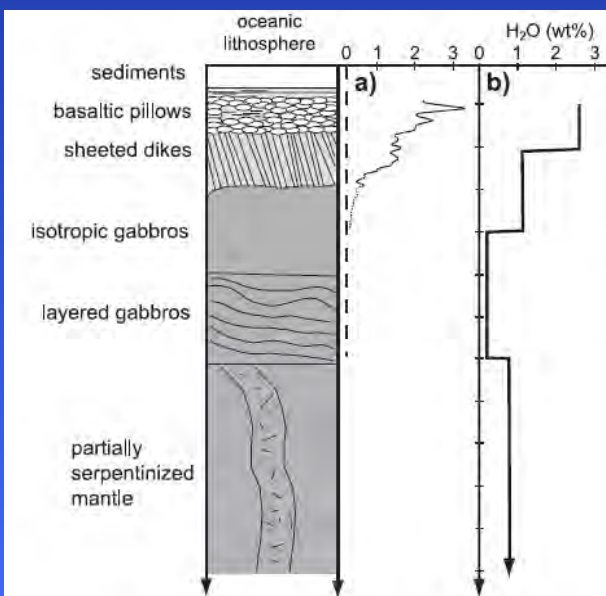
Van Avendonk et al. (Gcubed, 2011)

Water budget of subduction zones





Klaucke et al. (G-Cubed, 2008)



Ruepke et al. (EPSL, 2004)

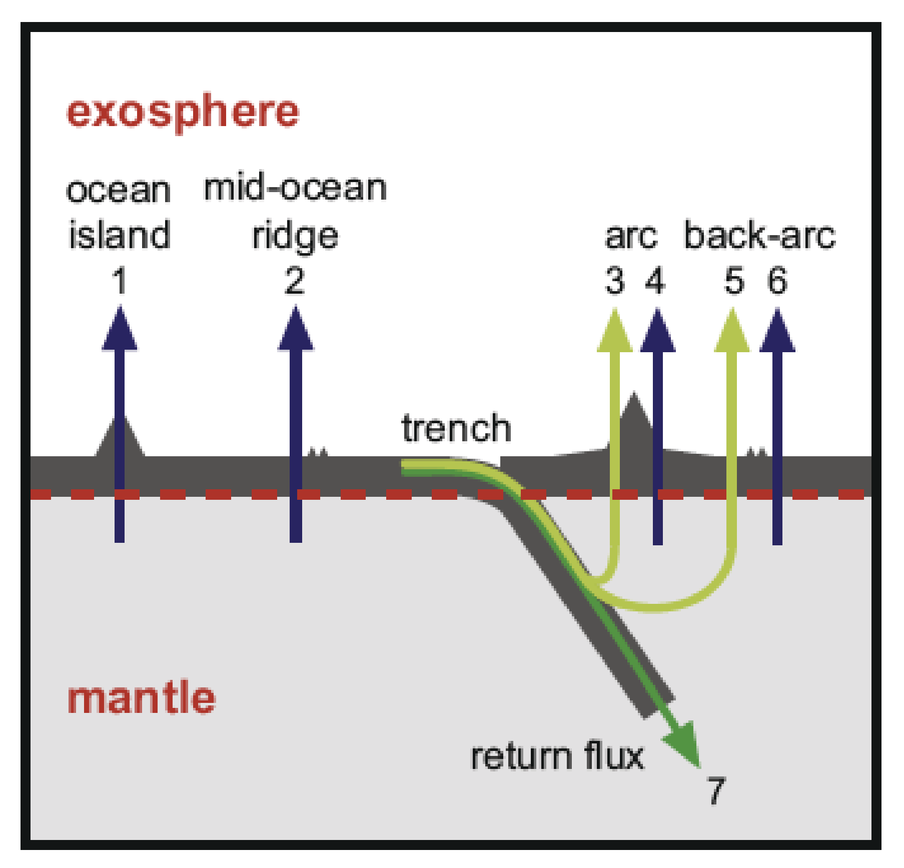
- ➢ H_2O input from sediments, crust, and oceanic mantle of subducting plate
- ➢ Sediments lose water early by compaction
- ➢ Mantle contains chemically bound water (serpentinite) that may be delivered to arc depths or deeper

Large H_2O fluxes:

➢Current estimate of H2O subduction 7 times larger than what we need for stable sea level over last 500 Myr.

➢A maximum 2-3% serpentinization of the top 10 km of oceanic lithosphere can explain a 360 m decrease of sea level in the Phanerozoic.

➢Degassing of the mantle must also be quantified



Parai and Mukhopadhyay (2012)

Conclusions

- Different styles of subduction in Central America. Coincidentally, geochemical slab tracers increase strongly from Costa Rica to Nicaragua.
- Shallow subduction angle of Cocos plate beneath Costa Rica consistent with presence of thicker crust .
- Anomalous crust near Cocos Ridge can account for geochemical enrichment, and lower Ba/La, B/La, towards CR/NIC border.
- Mantle beneath EPR crust offshore Nicaragua is likely serpentized up to 25%, 12 km beneath Moho
- Water input from deep ocean lithosphere offshore Nicaragua larger than offshore Costa Rica.
- Plausible explanation for some geochemical trends (Ba/La, B/La) from CR/NIC border to NW Nicaragua.

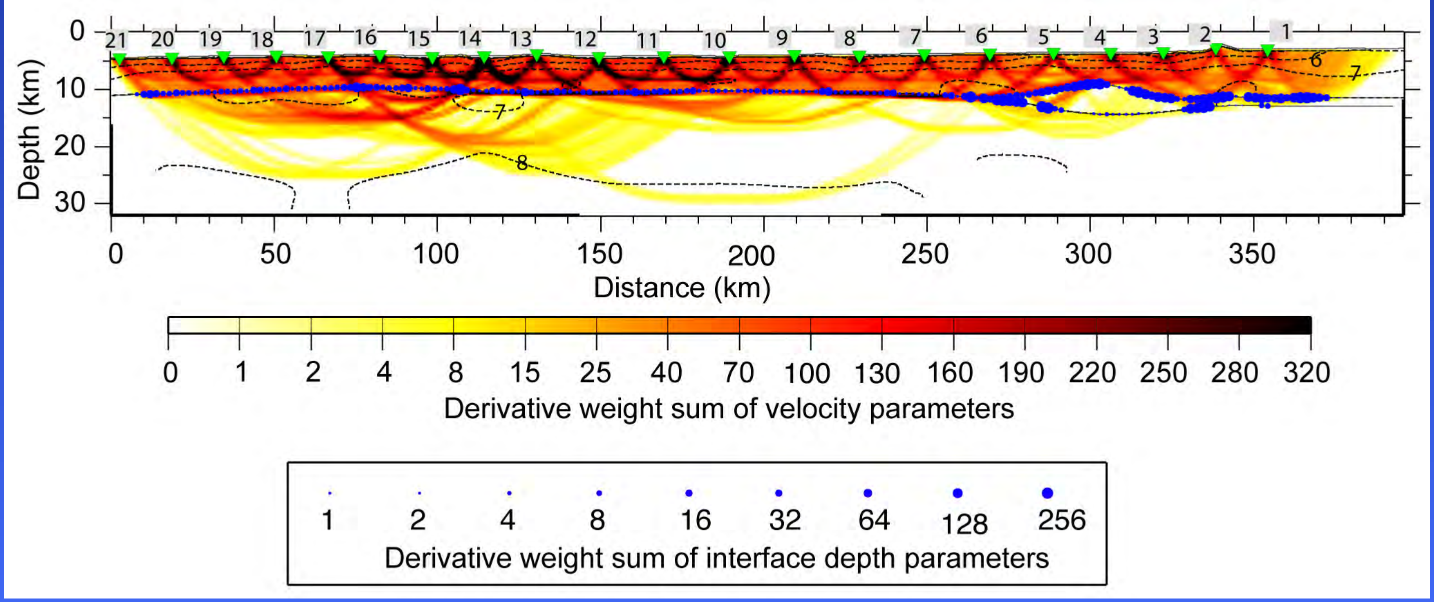
The end

Ray density (Derivative weight sum)

Ray density weighted by traveltime uncertainty

Offers first impression of model constraints

Crust is sampled much better than upper mantle



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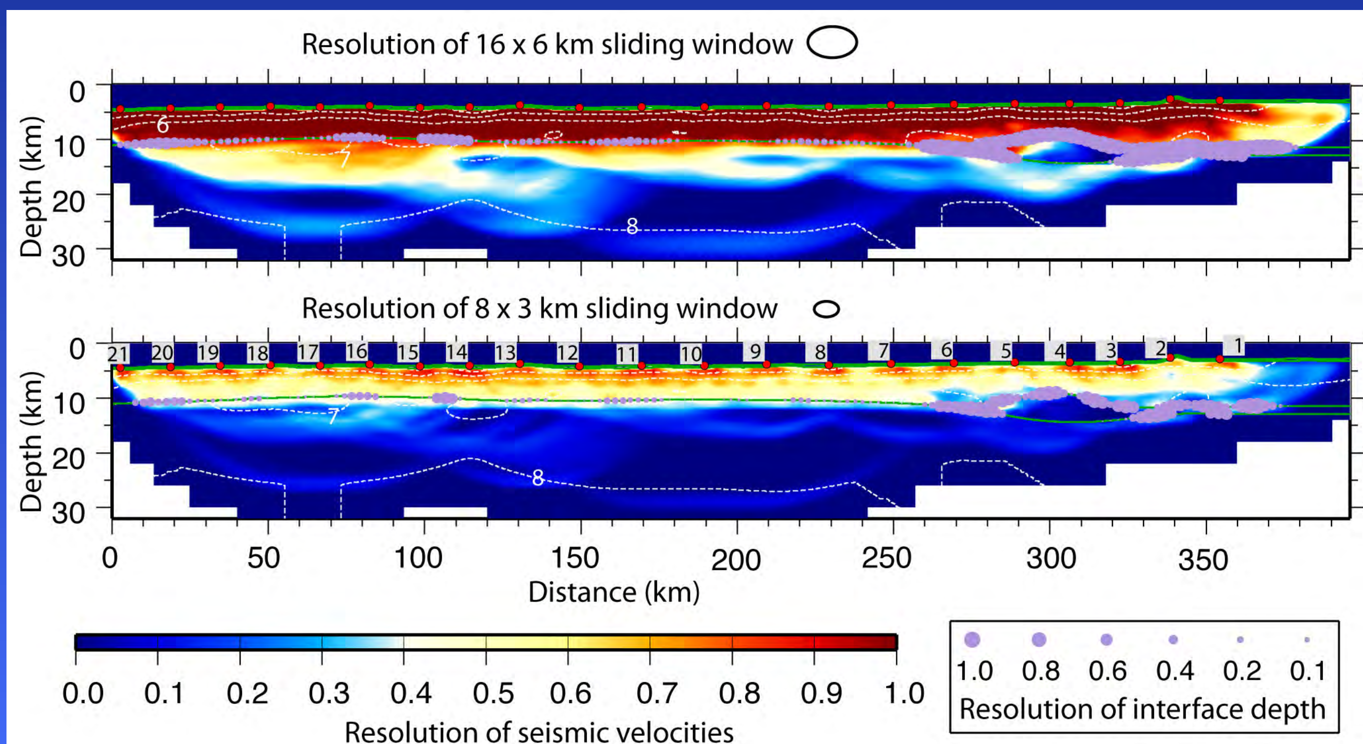
Resolution matrix

Shows model distortion at different length scales

Large features are best resolved

Crust and mantle are averaged over different length scales



Data fit of OBS 2, CN crust

Complicated Moho and mid-crustal reflections

Weak mantle phases

Thick crust with relatively low seismic velocities