Using seismic tomography to image subduction systems: Applications to Costa Rica-Nicaragua and Sumatra

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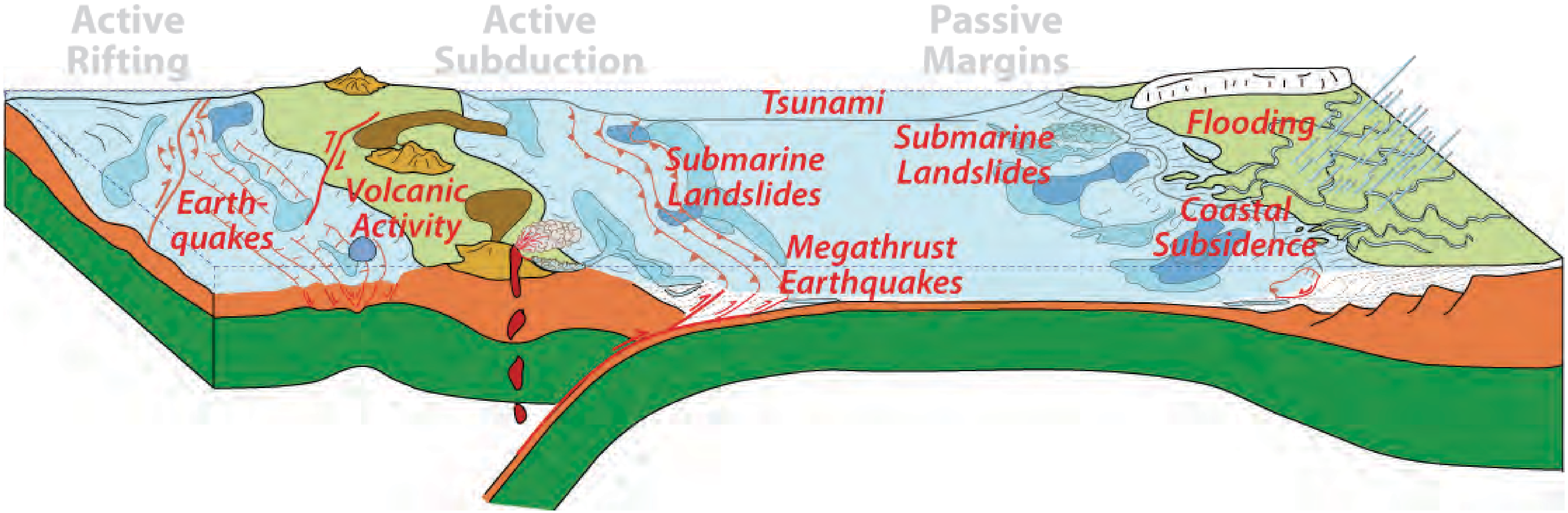
GeoPRISMS DLP

Univ. of Alabama
Jan. 30th, 2013

NSF GeoPRISMS Program



***GeoPRISMS investigates the coupled geodynamics, earth surface processes, and climate interactions that build and modify continental margins** over a wide range of timescales (from s to My), and cross the shoreline, with applications to margin evolution & dynamics, construction of stratigraphic architecture, accumulation of economic resources, and associated geologic hazards and environmental management.*

GeoPRISMS

Geodynamic Processes at Rifting and Subducting Margins

- **Successor to the decadal NSF MARGINS Program**
- **Studies of origin & evolution of continental margins**
  - Community-driven, interdisciplinary, cross-divisional NSF-funded
  - Integrating field, theory, experiment, and modeling
- **Focus on rifts and subduction zones**
  - Active geodynamic processes; formation of continental crust
  - Where geology and society intersect; many economic resources
- **Shoreline-crossing, i.e., “amphibious”**
  - Where most rifts and subduction zones occur
  - Geologic & geodynamic processes span the shoreline
  - Where focused, cross-divisional efforts most needed

GeoPRISMS Geodynamic Processes at Rifting and Subducting Margins

- **Two broadly integrated initiatives**

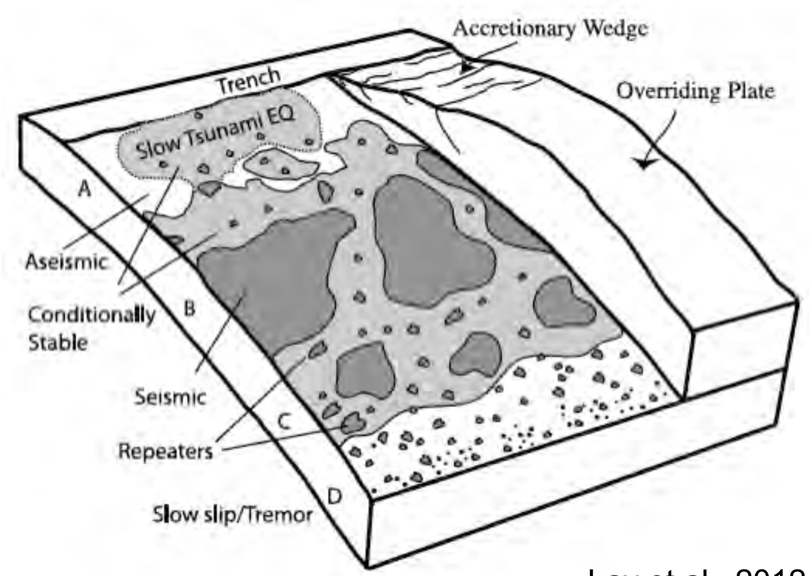
Subduction Cycles & Deformation

Rift Initiation & Evolution

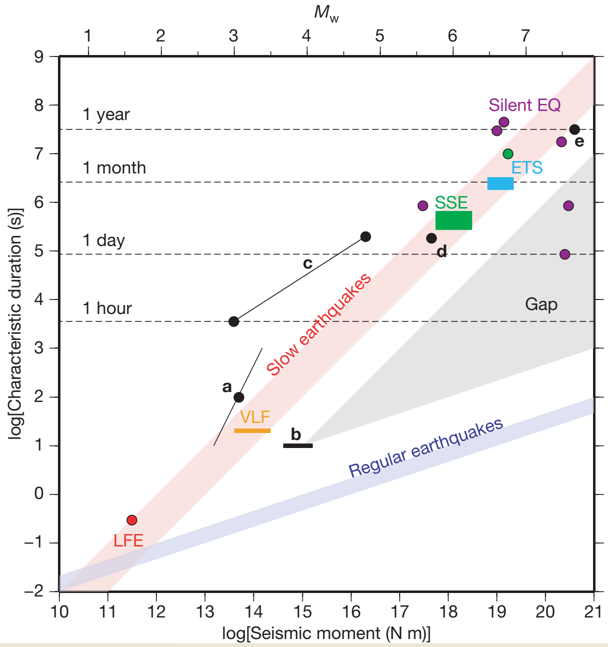
- **Research at Primary Sites & through Thematic Studies**

SCD Key Questions

- What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?
- How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?



Lay et al., 2012

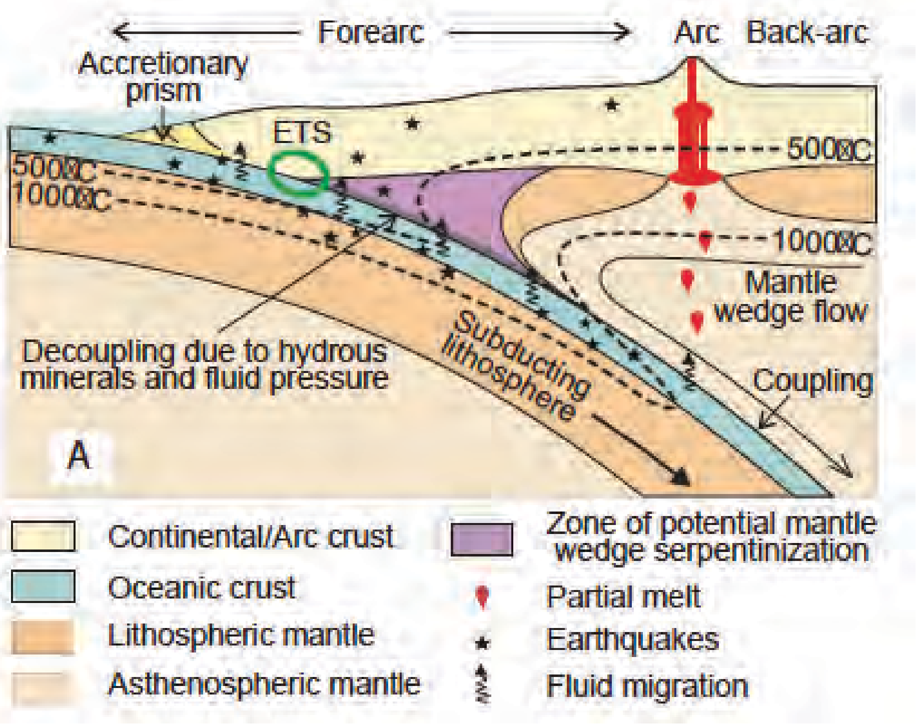


Ide et al. 2007

SCD Key Questions

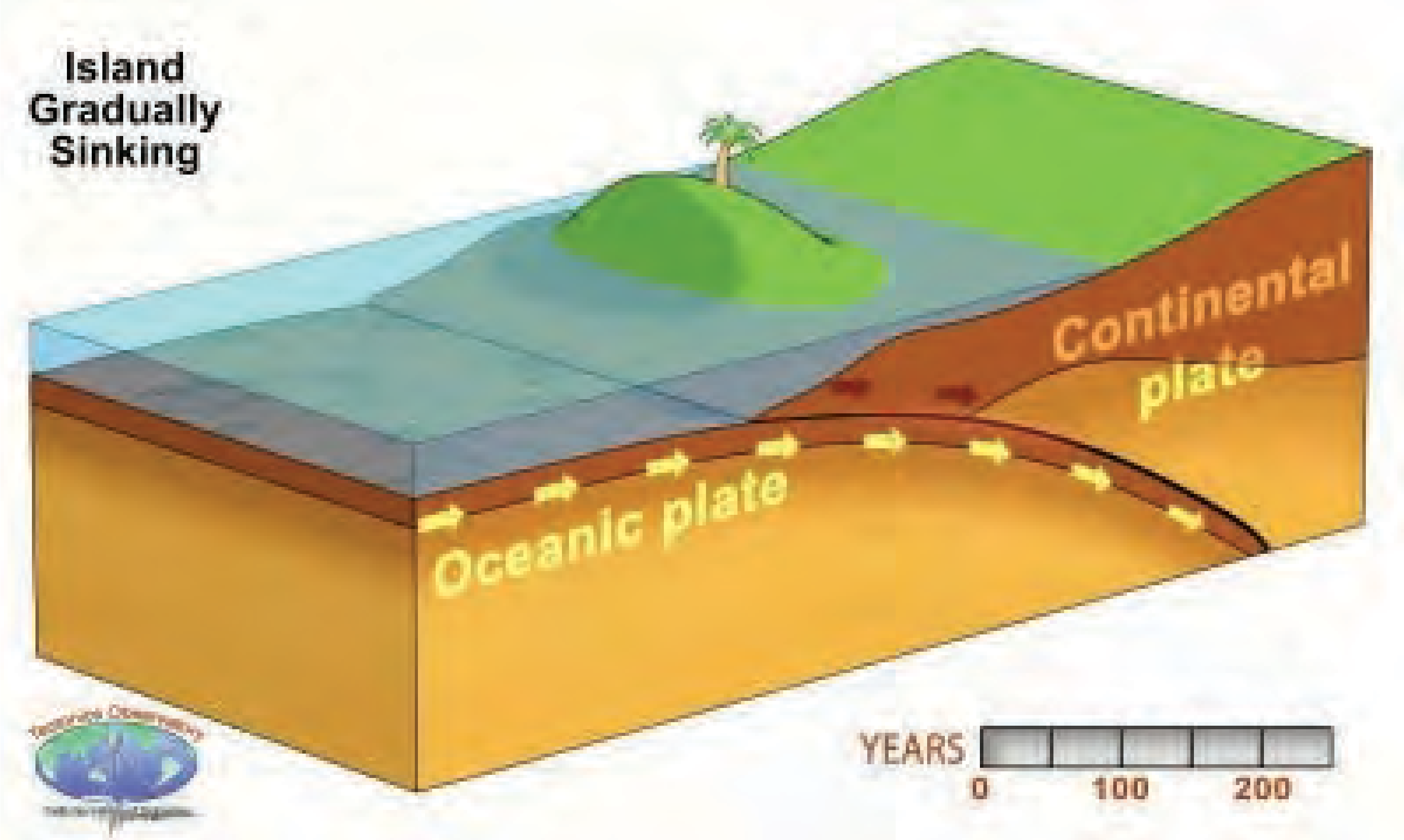
- How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench through to the arc and backarc?

- How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?



Wada and Wang, 2009

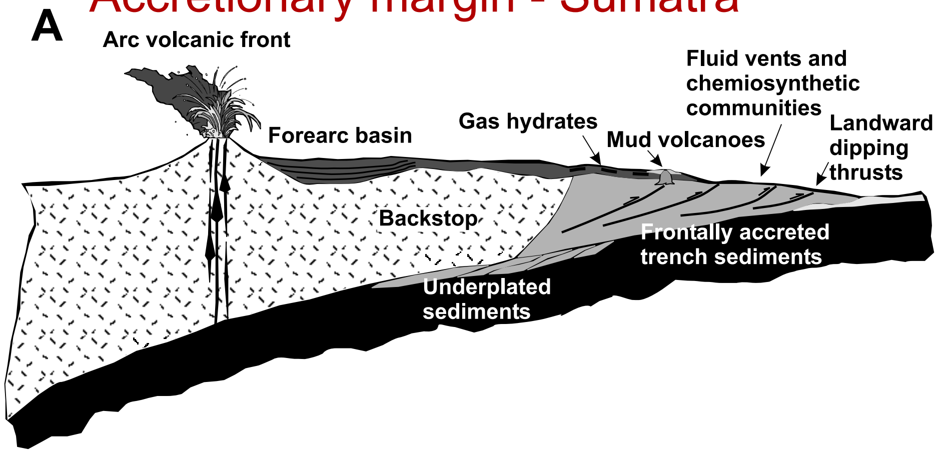
The megathrust and tsunamis



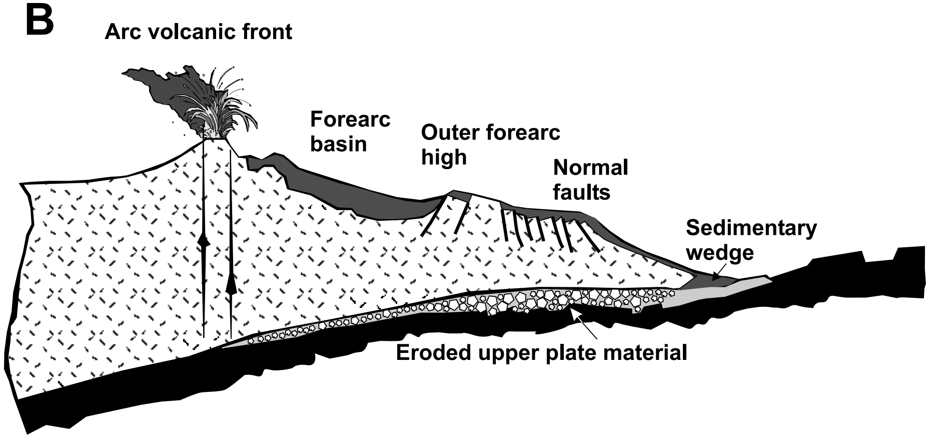
A comparison using relocation & tomography

- Sumatra
  - Great megathrust events
  - Very long subduction zone
  - Regional/teleseismic data
- Costa Rica/Nicaragua
  - No great earthquakes
  - Small, highly variable region
  - Local earthquake data

Accretionary margin - Sumatra

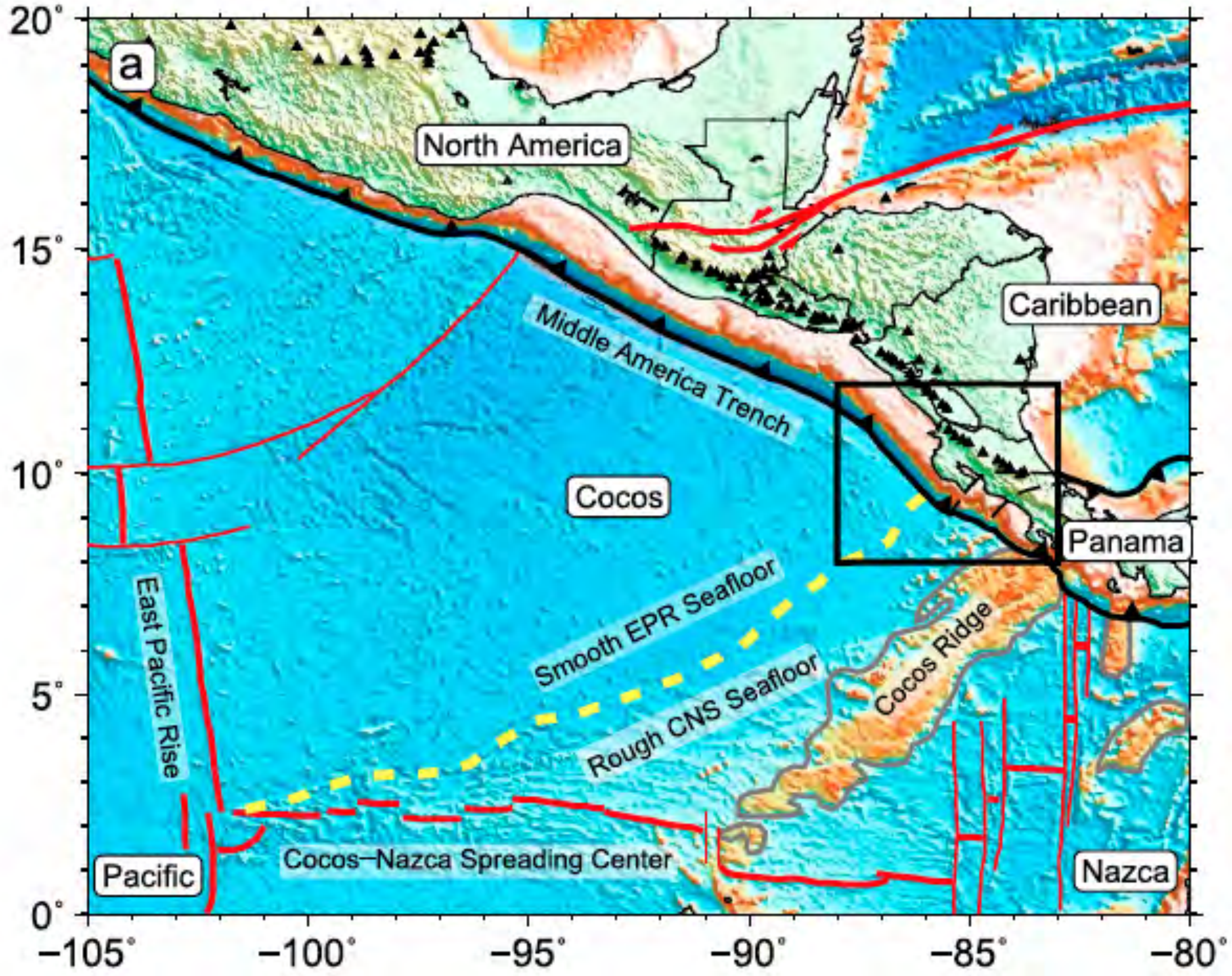


Erosional margin - Costa Rica/Nicaragua



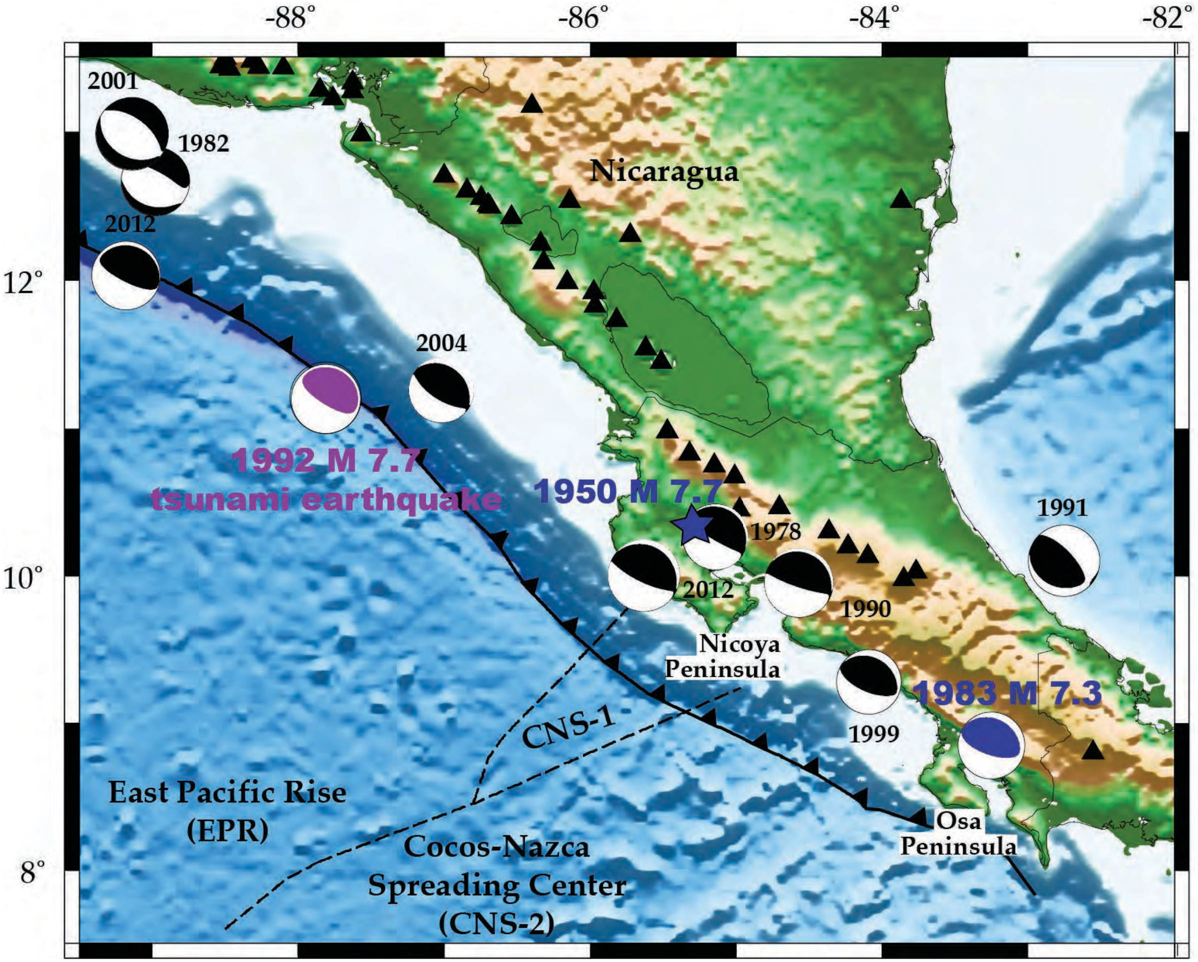
Clift and Vannucchi, 2004

Costa Rica/Nicaragua, Middle America

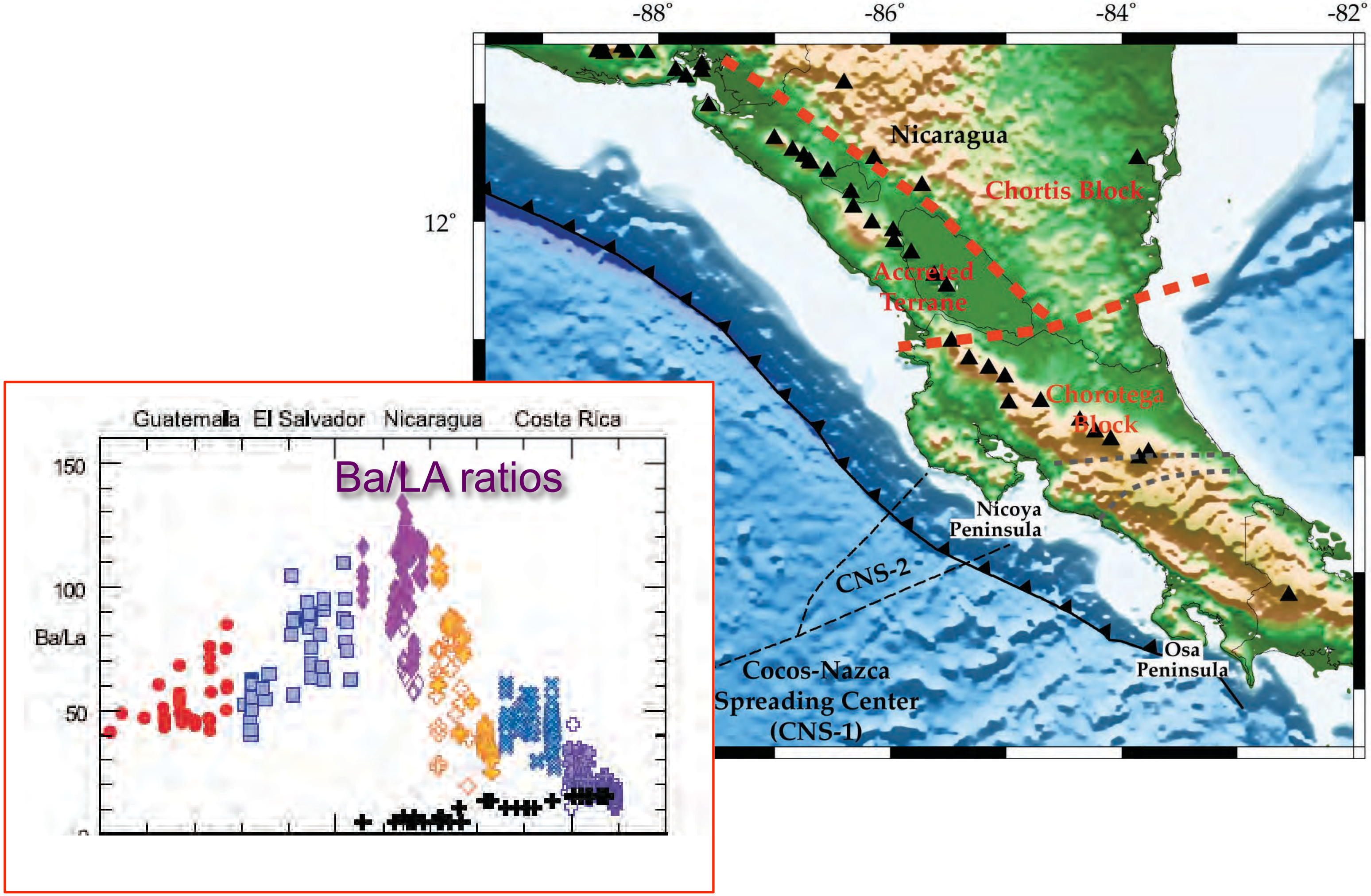


Feng et al., 2012

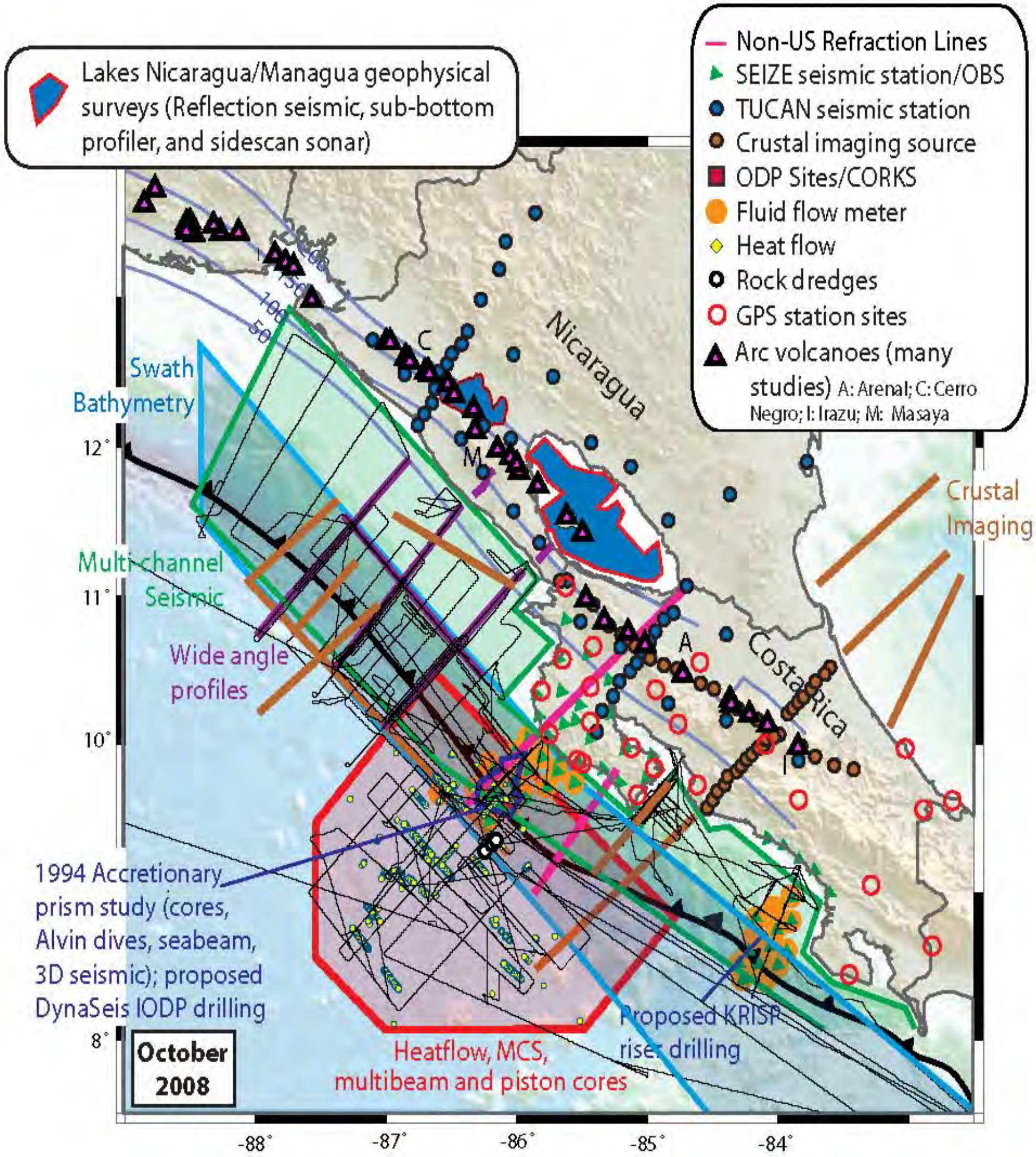
History of significant earthquakes

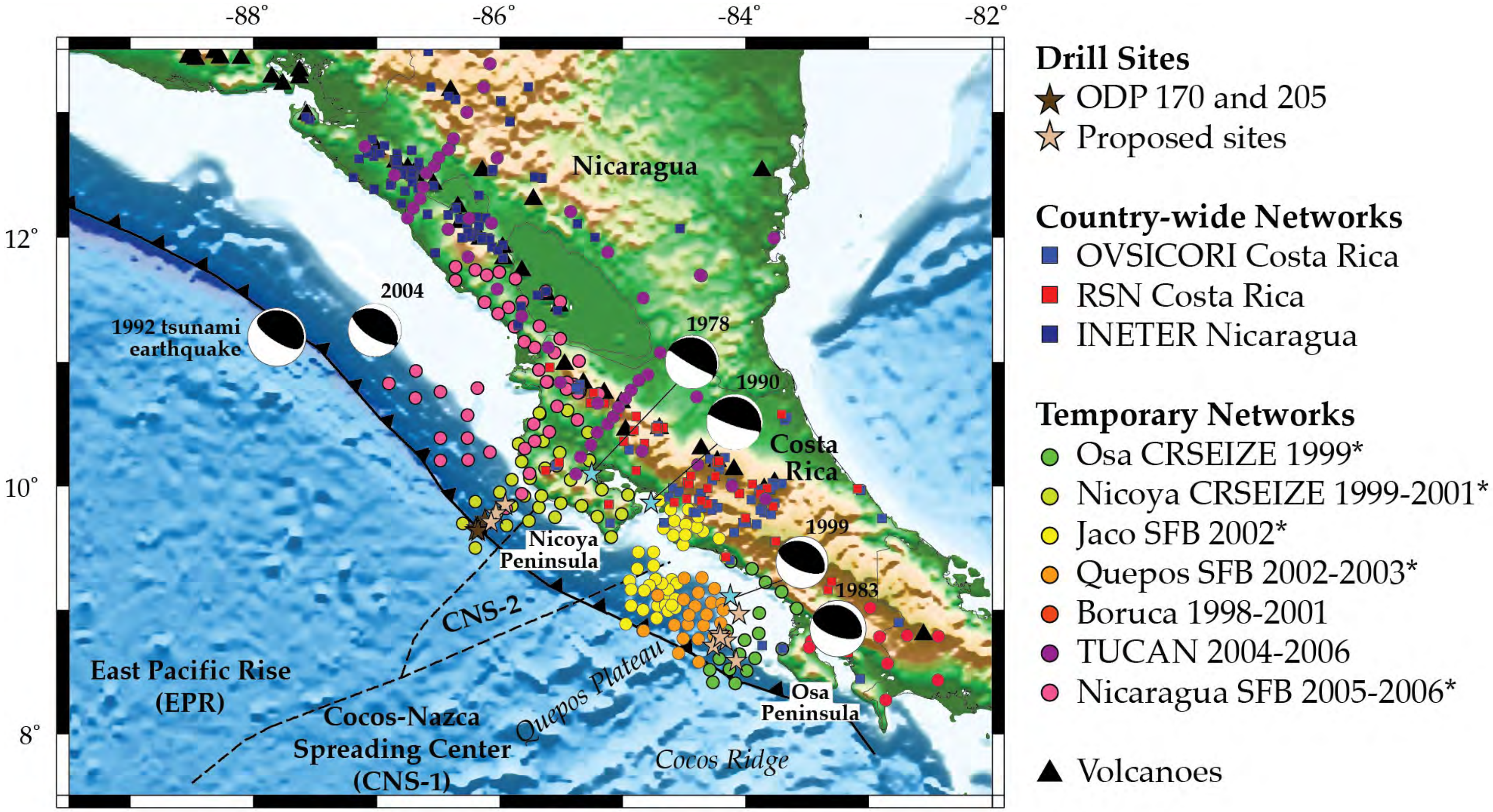


Along-strike variation



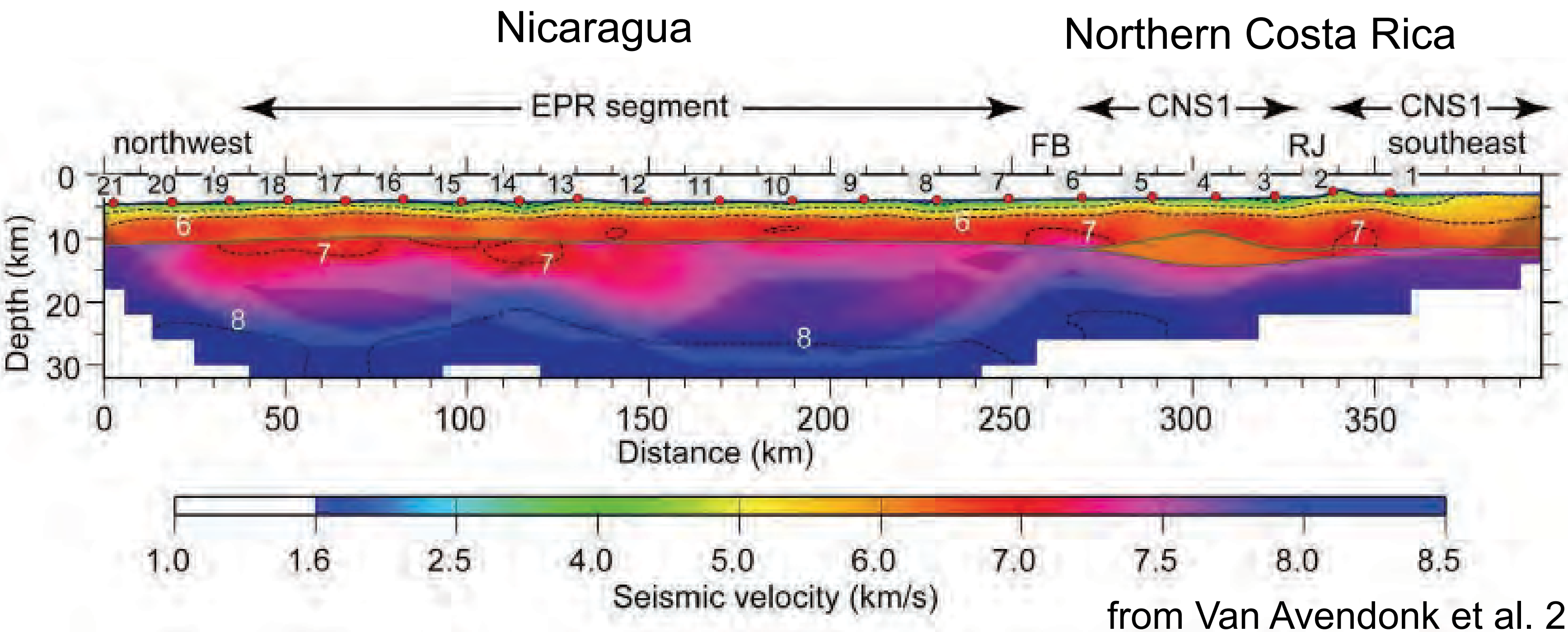
An NSF Margins and German SFB Focus Site




-88°
-86°
-84°
-82°
12°
10°
8°
Nicaragua
2004
1992 tsunami earthquake
1978
1990
Costa Rica
1999
1983
Nicoya Peninsula
CNS-2
East Pacific Rise (EPR)
Cocos-Nazca Spreading Center (CNS-1)
Quepos Plateau
Cocos Ridge
Osa Peninsula
Drill Sites
ODP 170 and 205
Proposed sites
Country-wide Networks
OVSICORI Costa Rica
RSN Costa Rica
INETER Nicaragua
Temporary Networks
Osa CRSEIZE 1999*
Nicoya CRSEIZE 1999-2001*
Jaco SFB 2002*
Quepos SFB 2002-2003*
Boruca 1998-2001
TUCAN 2004-2006
Nicaragua SFB 2005-2006*
Volcanoes

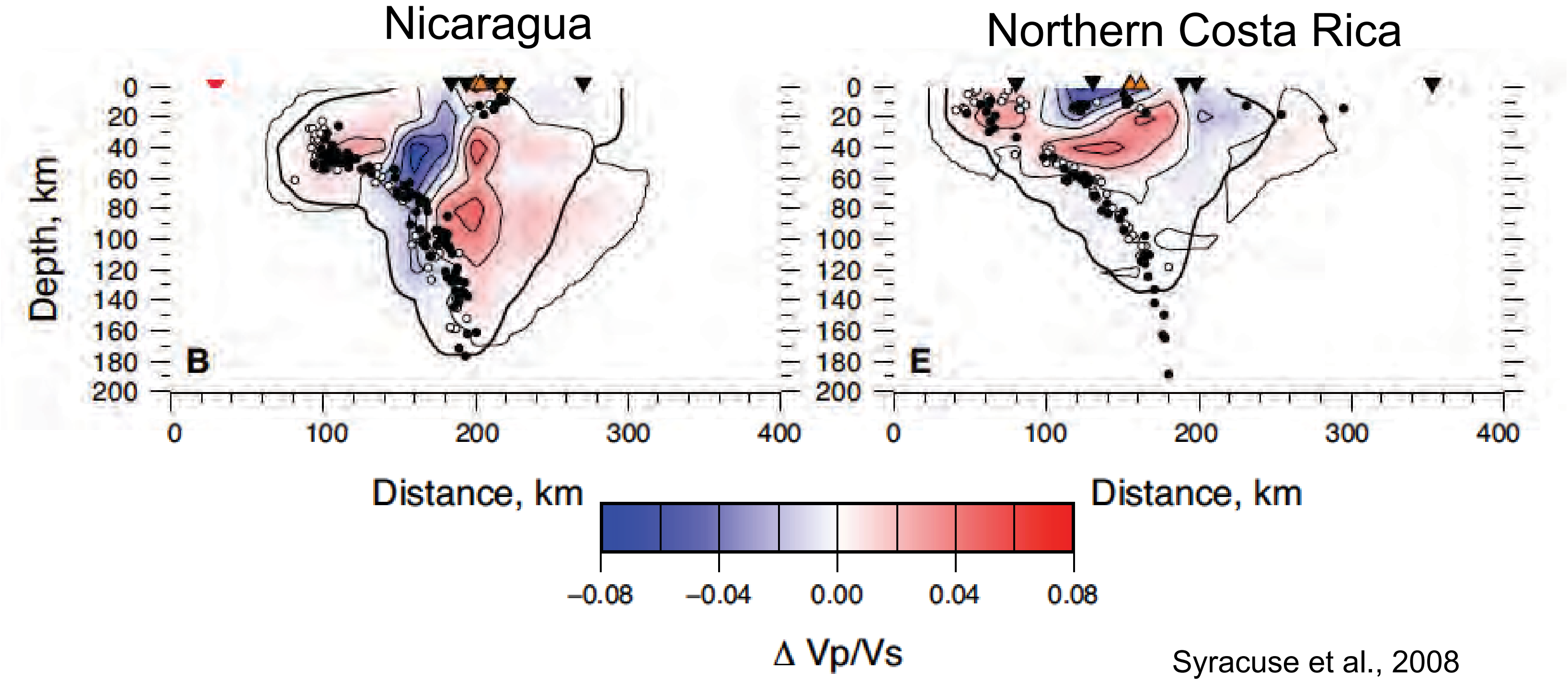
- Oceanic plate varies in age and morphology. Changes in temperature and/or pore fluid pressure along-strike spatially correlate with changes to the updip limit of seismogenic zone microseismicity.

- Oceanic upper mantle is variably serpentinized, allowing for significant fluid input into the subduction system at depth (i.e.., Grevemeyer et al., 2007; Syracuse et al., 2008; van Avendonk et al., 2011)



from Van Avendonk et al. 2011

- Large-scale differences in slab and wedge velocities and hypocenter distribution along Nicaragua and northern Costa Rica suggest the upper plate plays a critical role in subduction and volcanic processes (MacKenzie et al., 2008; Rychert et al., 2008; Dinc et al., 2010; etc)



Syracuse et al., 2008

- Characteristics of the oceanic plate largely influence rupture extent within the seismogenic zone. For example, seamount subduction controlled asperity locations the 1999 Quepos event.

- Downdip limit may be controlled by the presence of fluids along the plate interface or serpentinization of the mantle wedge (Van Avendonk et al., 2010; DeShon et al., 2006)

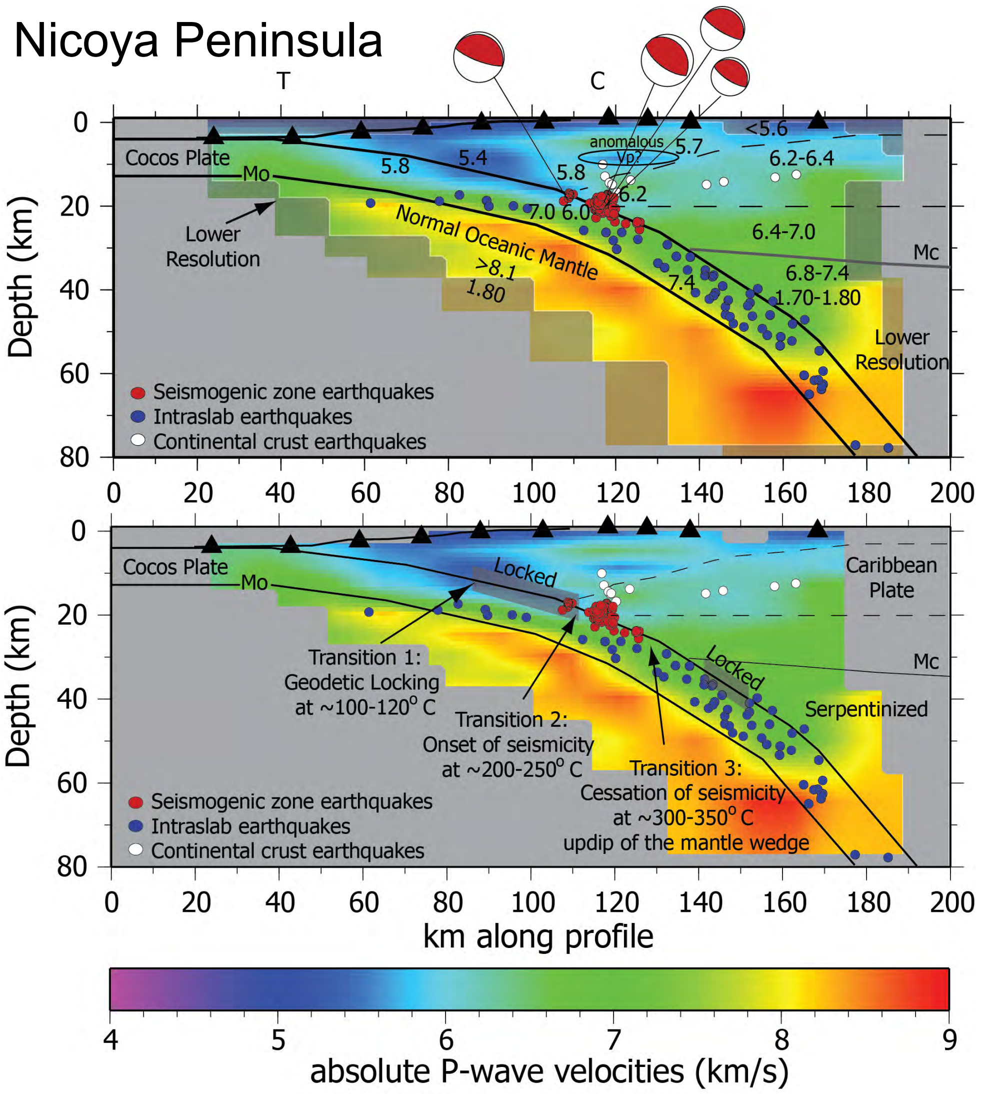
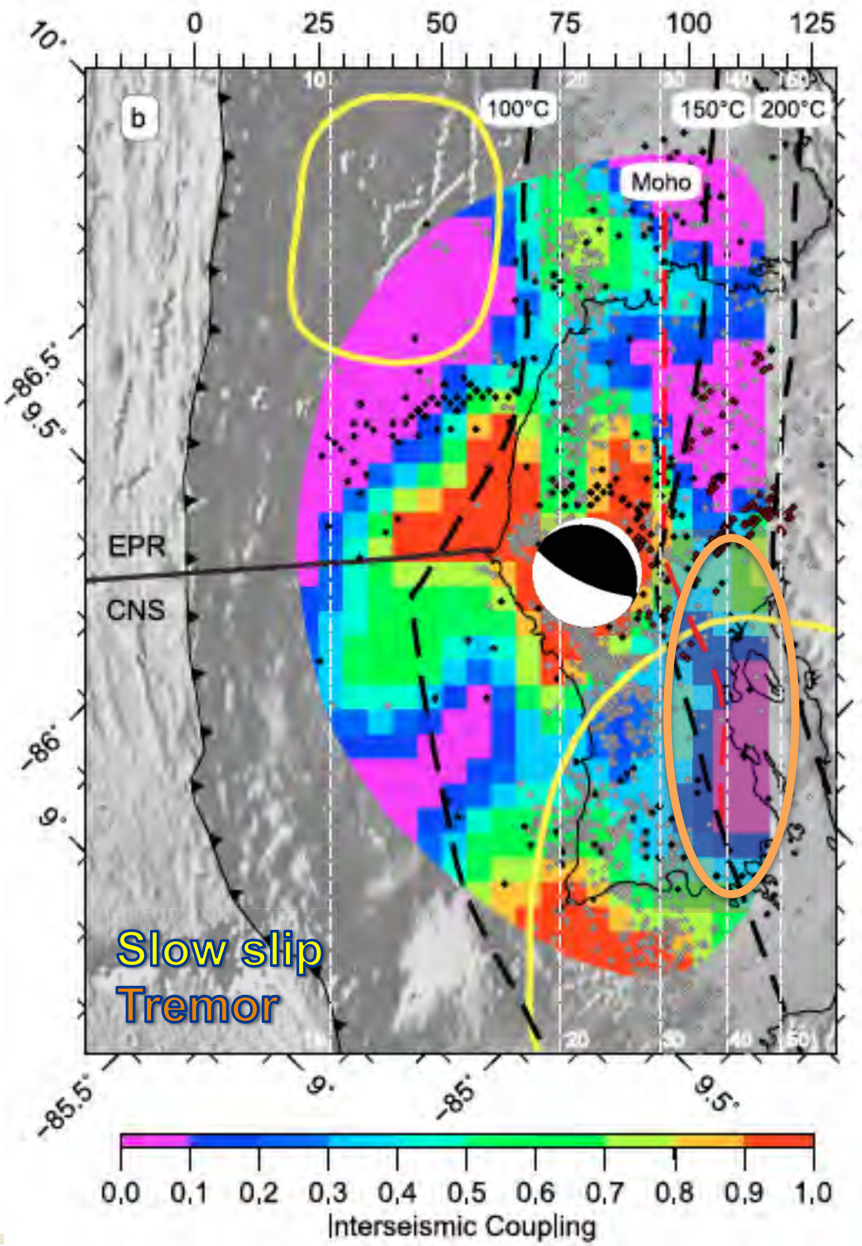


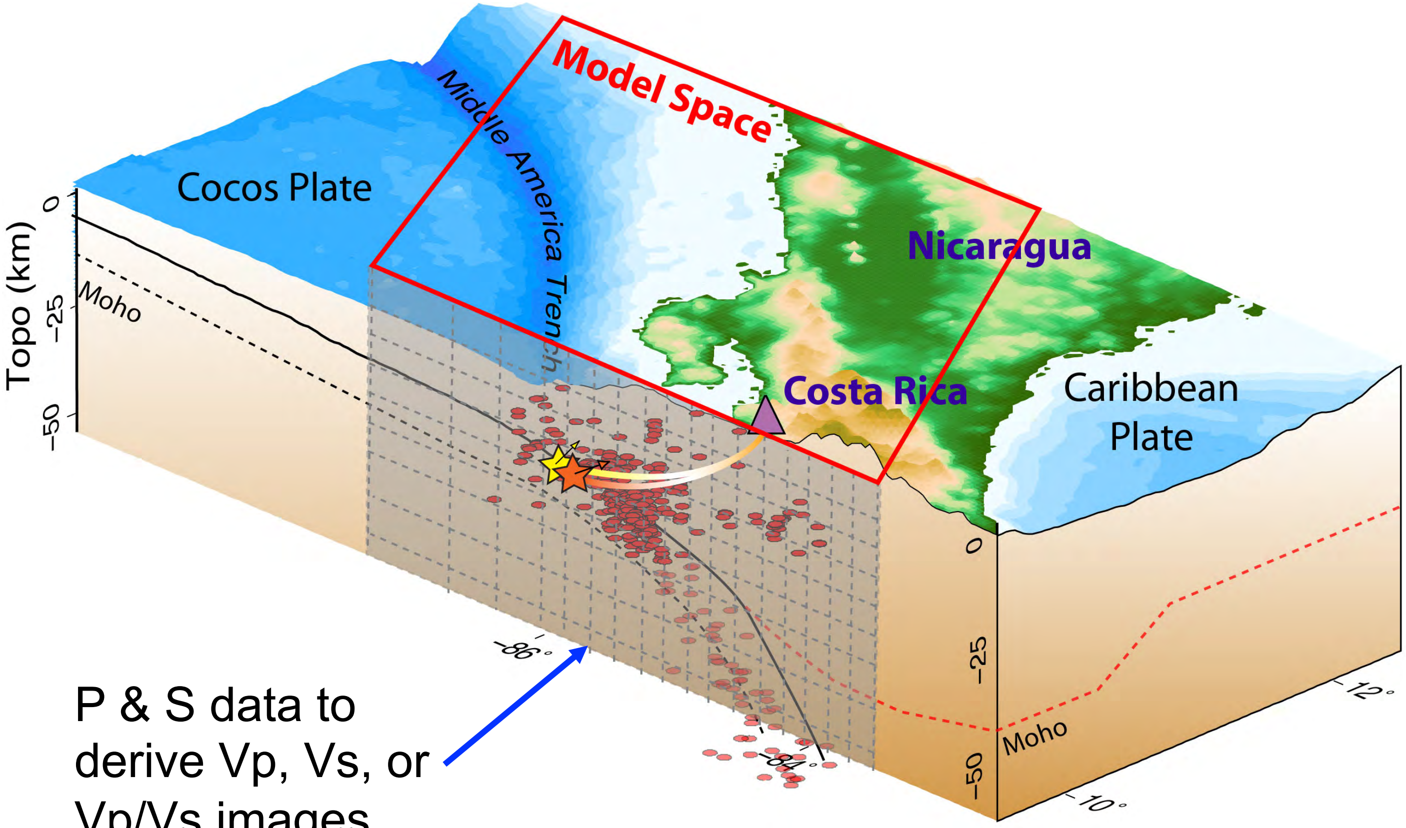
Image modified from DeShon et al. 2006; Schwartz and DeShon, 2007

- Geodetic modeling suggests highly variable locking along the megathrust (Norabuena et al., 2004; LaFemina et al., 2009; Feng et al., 2012)
- Tremor and slow slip processes have been identified at the updip and downdip edge of the seismogenic zone (Brown et al., 2005; Brown et al., 2009, Outerbridge et al., 2010, etc.)
- Geodesy, large magnitude earthquakes, thermal constraints and microseismicity constrain different seismogenic zone “limits.”



Feng et al., 2012

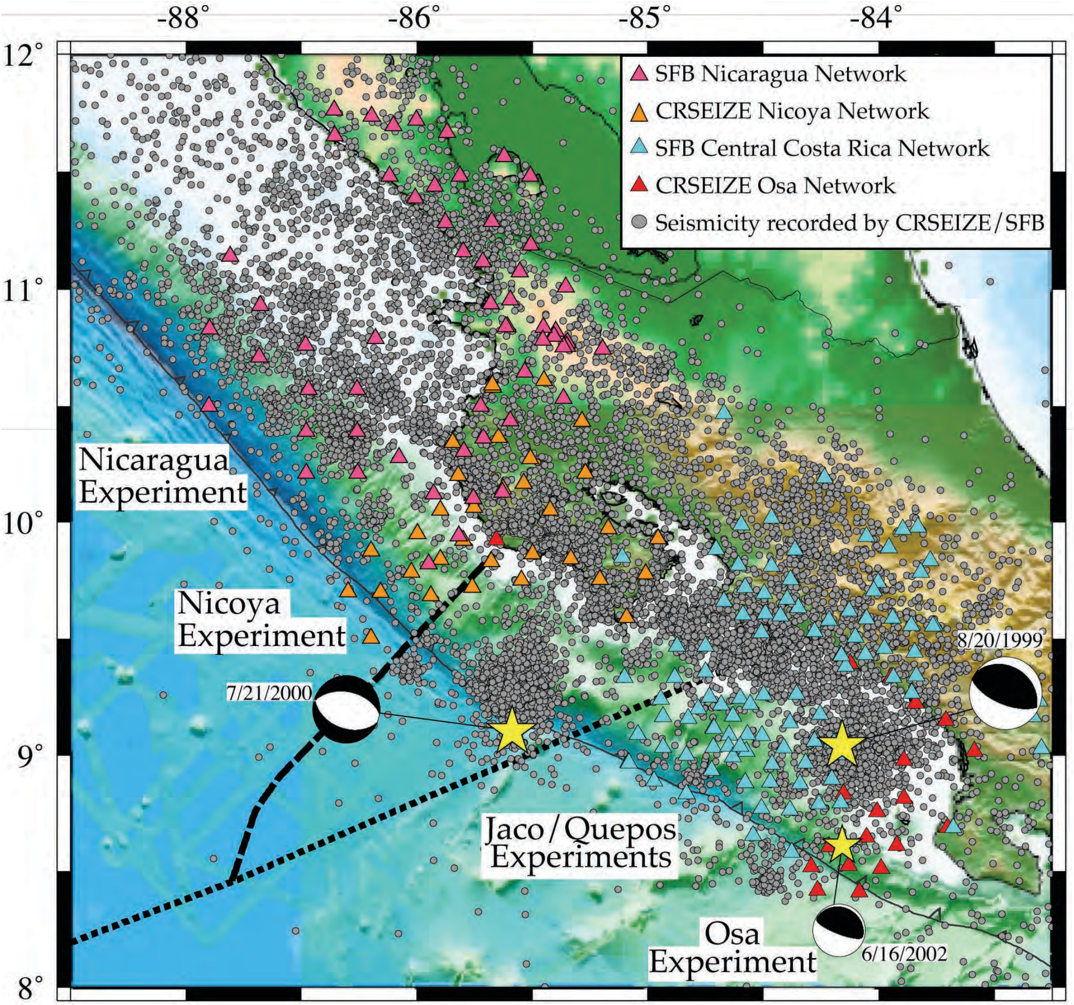
Double-Difference Tomography



P & S data to derive Vp, Vs, or Vp/Vs images

Absolute times, differential times, and waveform cross-correlation differential times

Data and Model Setup



Osa CRSEIZE
2 months 1999

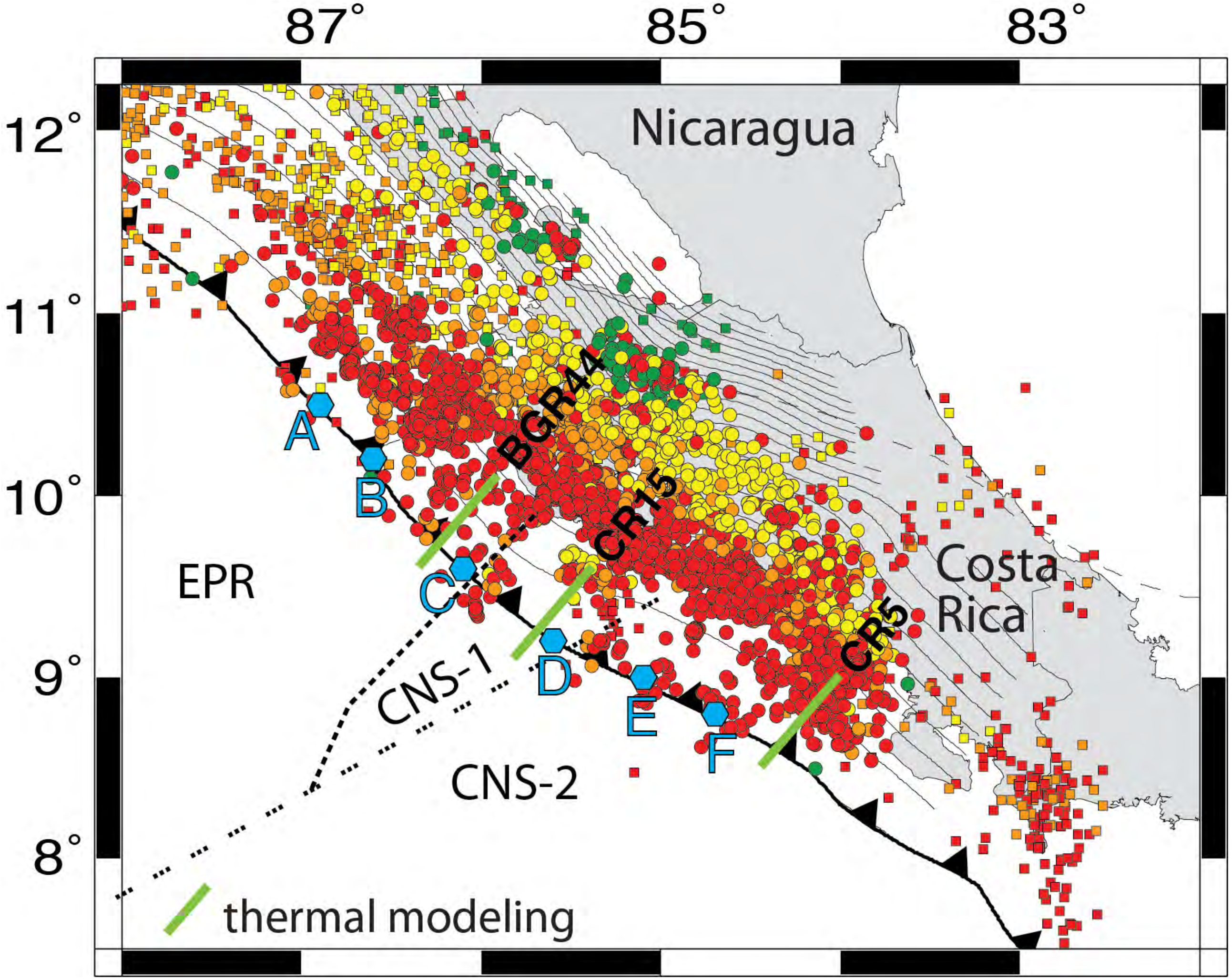
Nicoya CRSEIZE
1.5 years 1999-2001

Jaco & Quepos SFB
~1 year 2002-2003

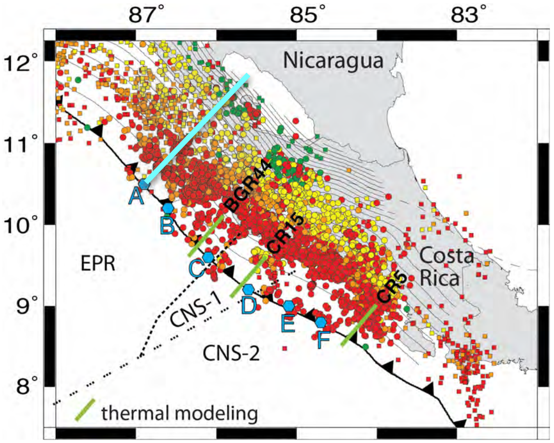
Nicaragua SFB
8 months 2005-2006

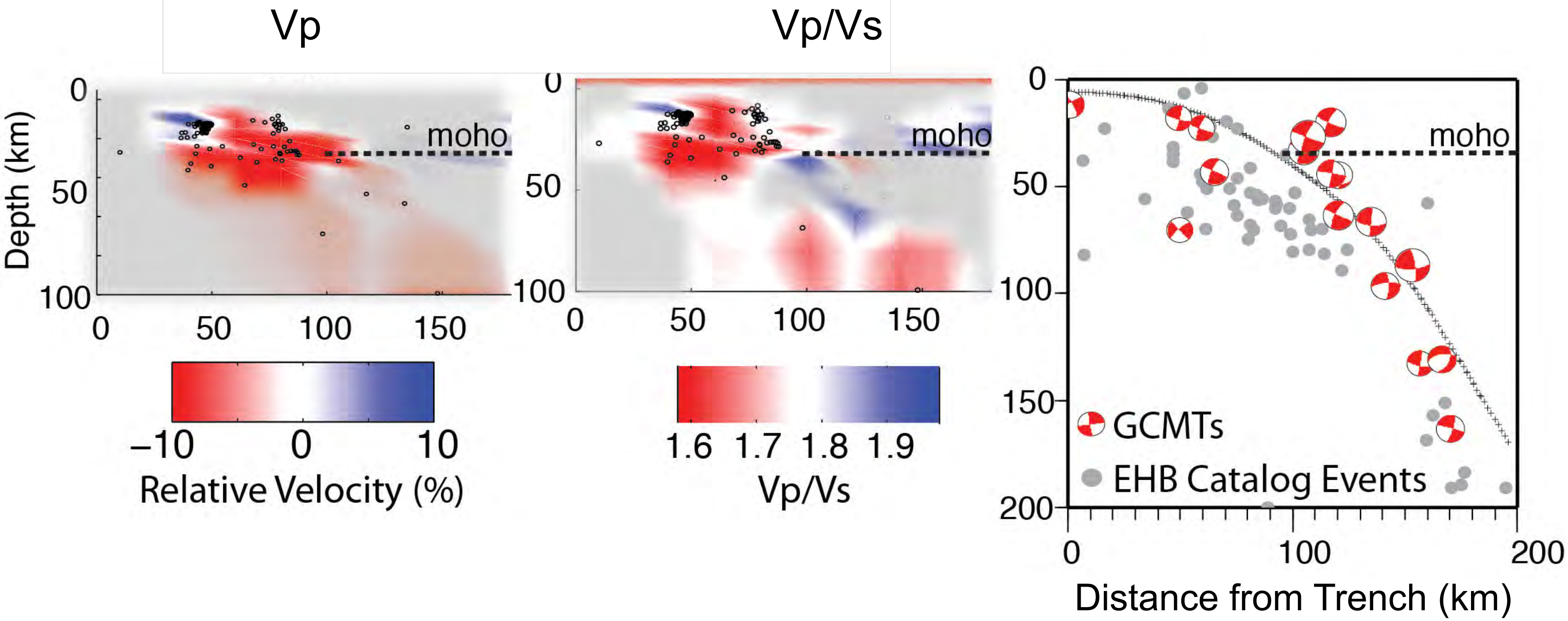
Results from Melissa Moore-Driskell, U. Memphis Ph.D. dissertation, 2012

Cross-section locations



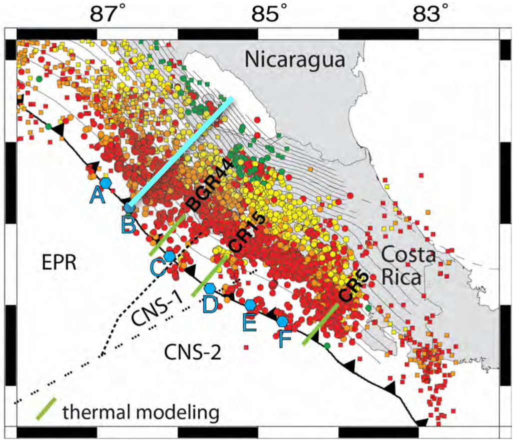
A: Southern Nicaragua

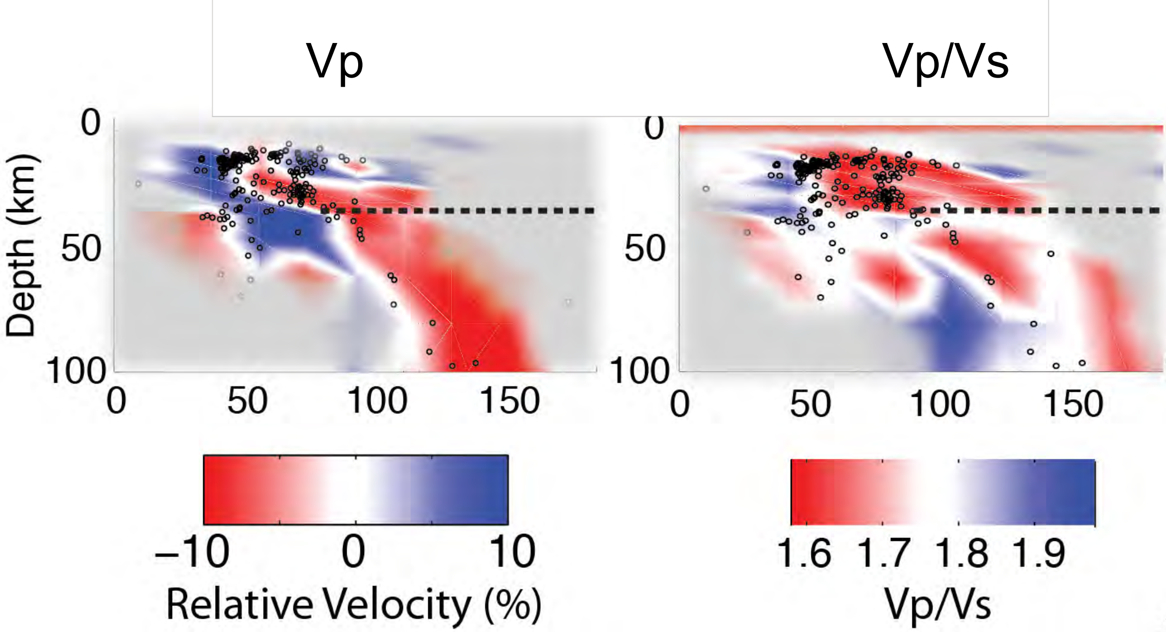


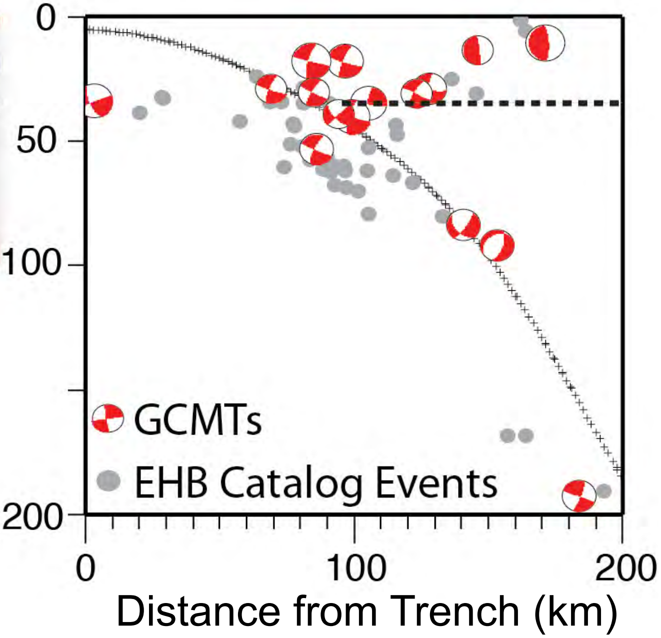


1. Slow slab P-wave velocities consistent with active source data

B: Santa Elena Peninsula

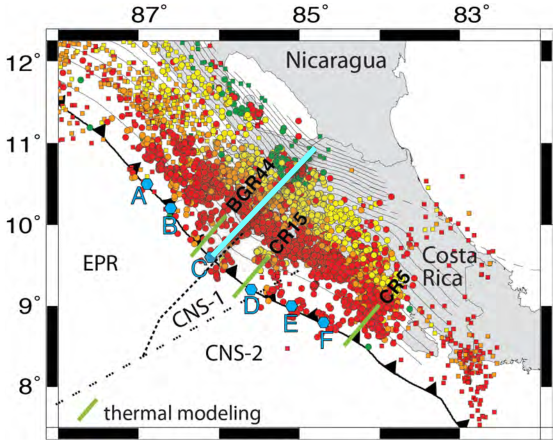


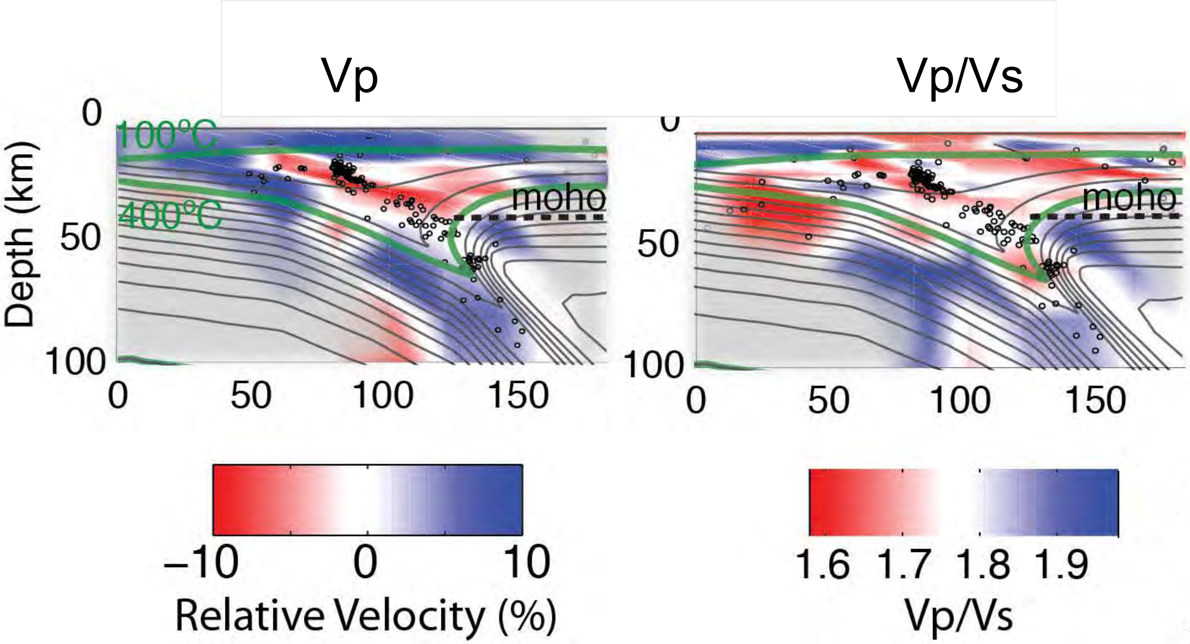


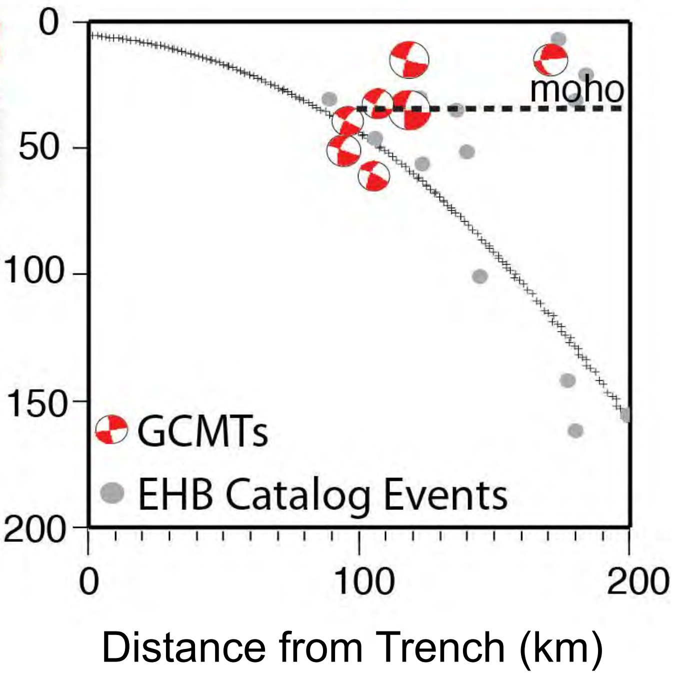


2. Abrupt transition to a fast slab and a more continuous seismogenic zone associated with reduced Vp.

C: Northern Nicoya BGR44 Heat Flow data



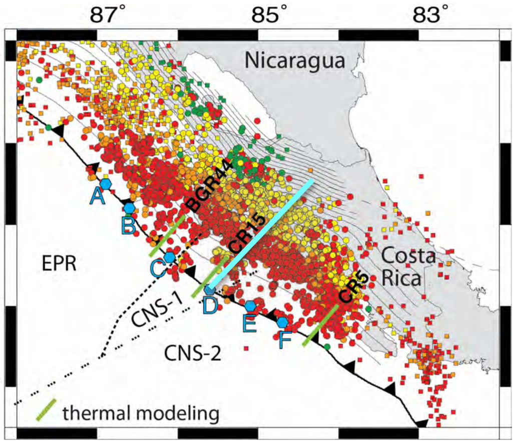


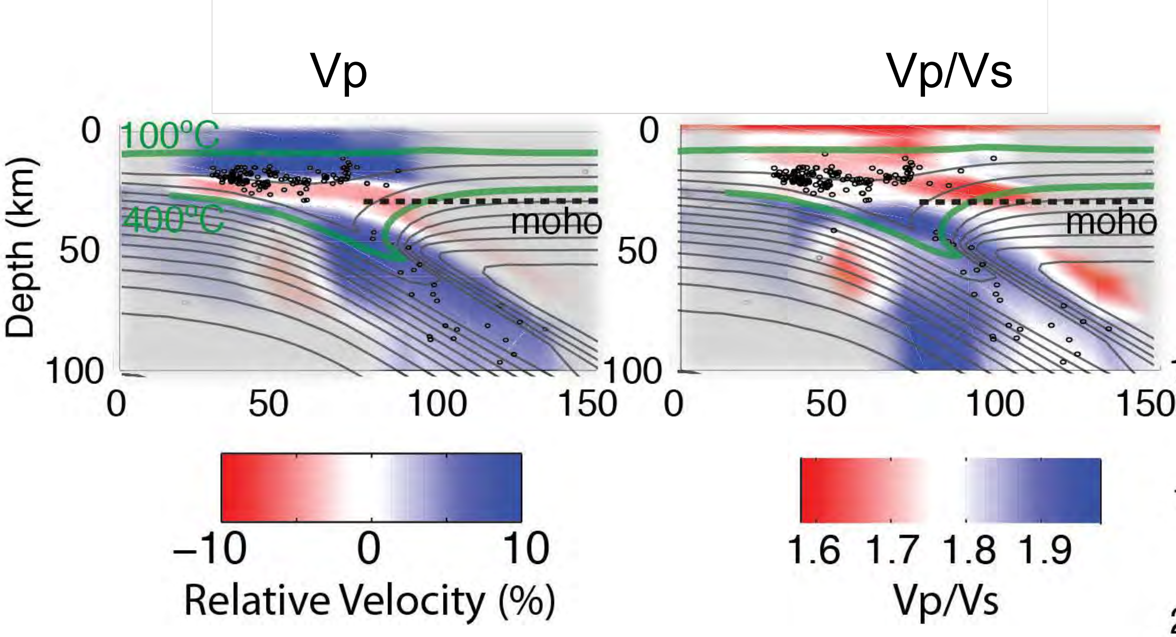


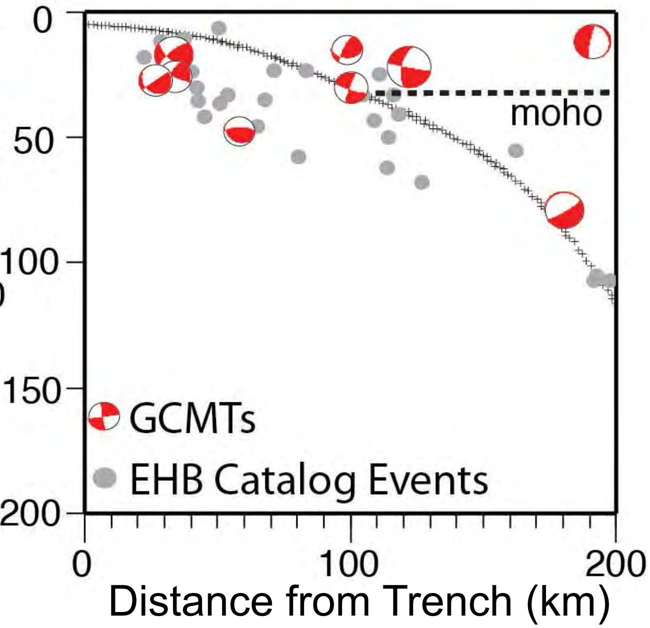
3. Narrowing of the microseismically defined seismogenic zone, though Vp anomaly remains broad.

Thermal model provided by Rob Harris

D: Southern Nicoya CR15 Heat Flow data



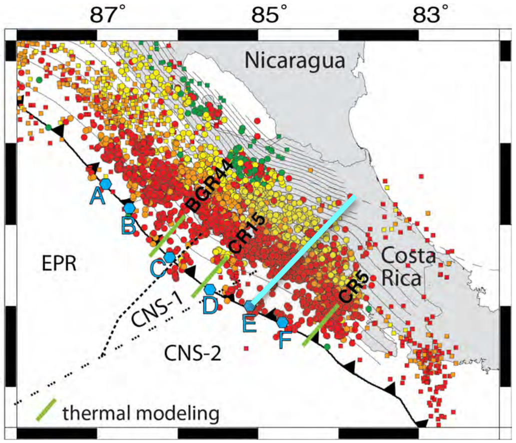


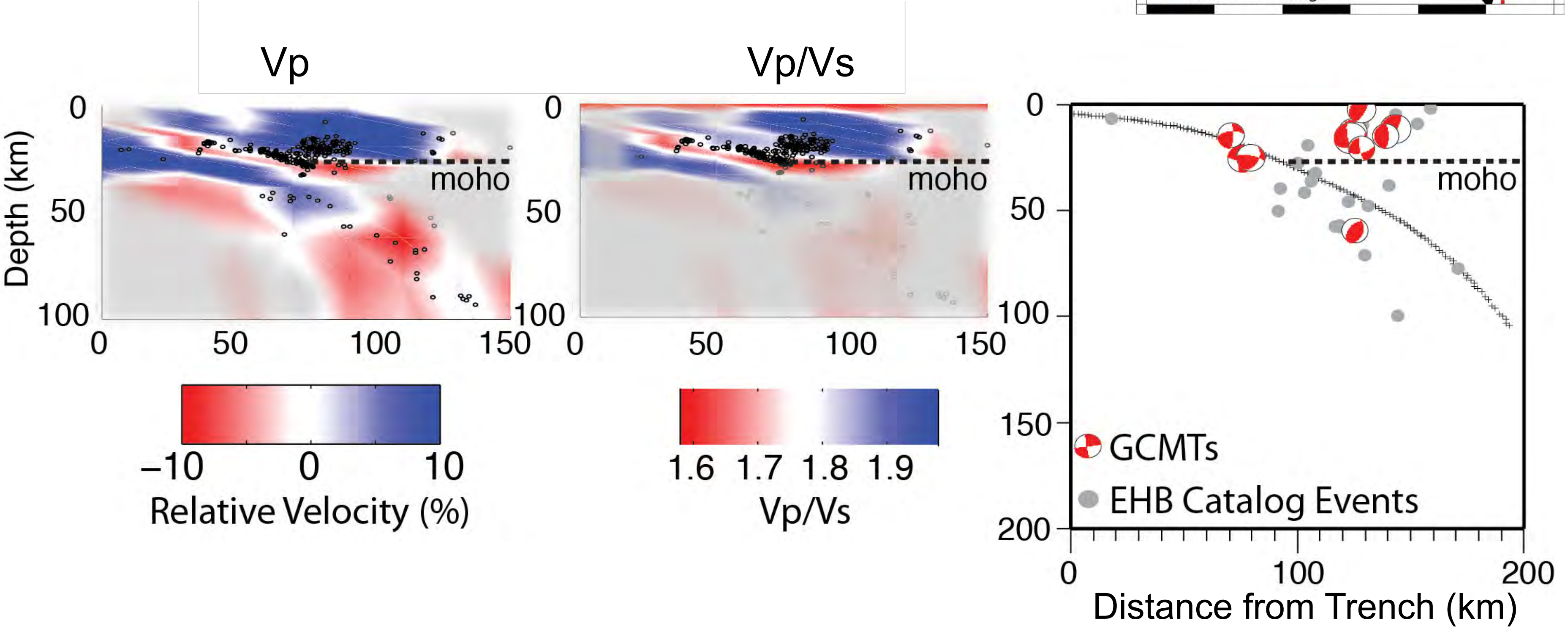


4. Imbricated seismogenic zone limited at the downdip edge by high Vp/Vs

Thermal model provided by Rob Harris

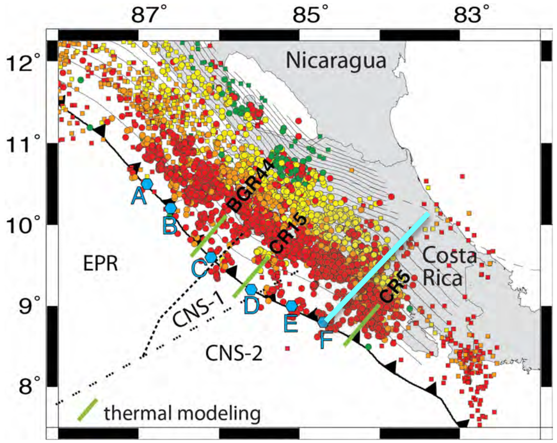
E: Central Costa Rica, offshore Jaco

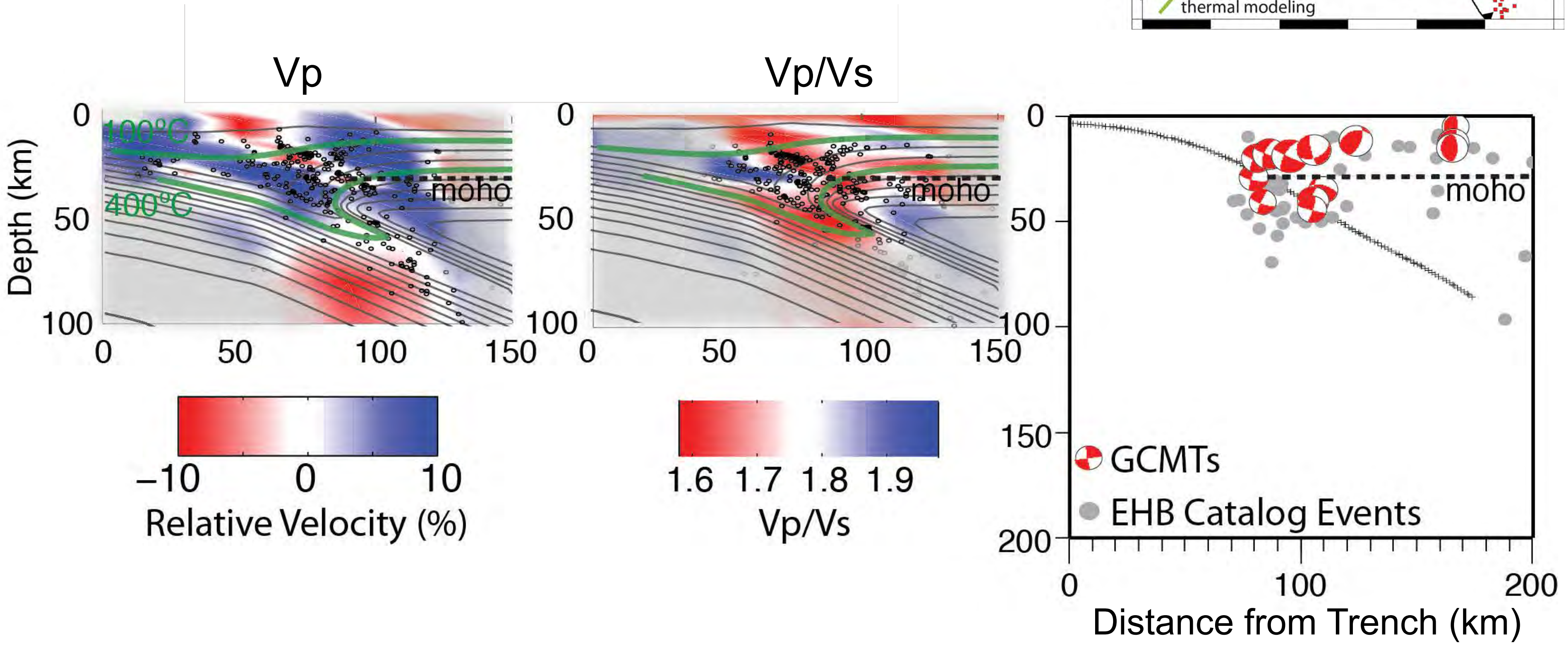




4. Broad, very thin seismogenic zone associated with extensive upper plate faulting just at or above the Moho

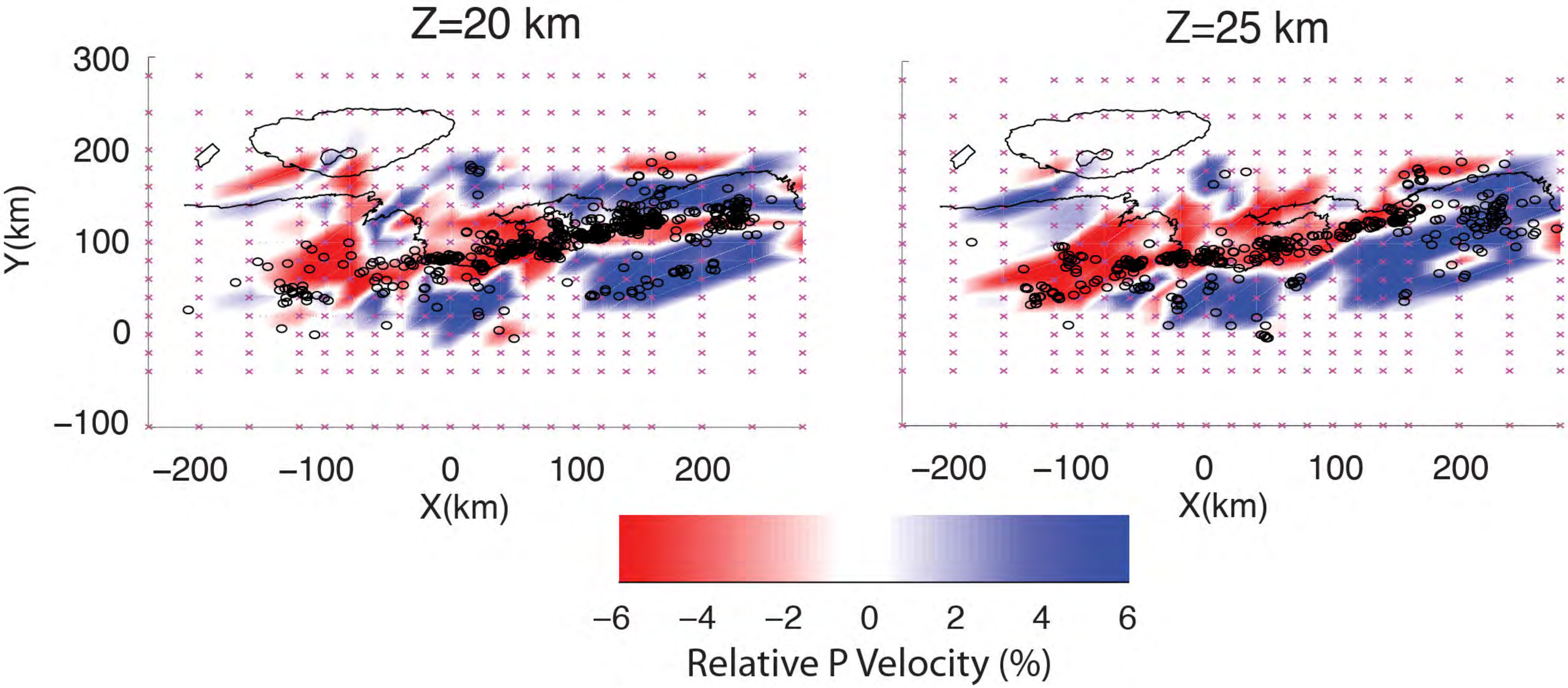
F: 1999 Quepos Aftershock Sequence CR5 heat flow data





5. Temperature limited seismogenic zone with extensive intraplate faulting, including along the outer rise

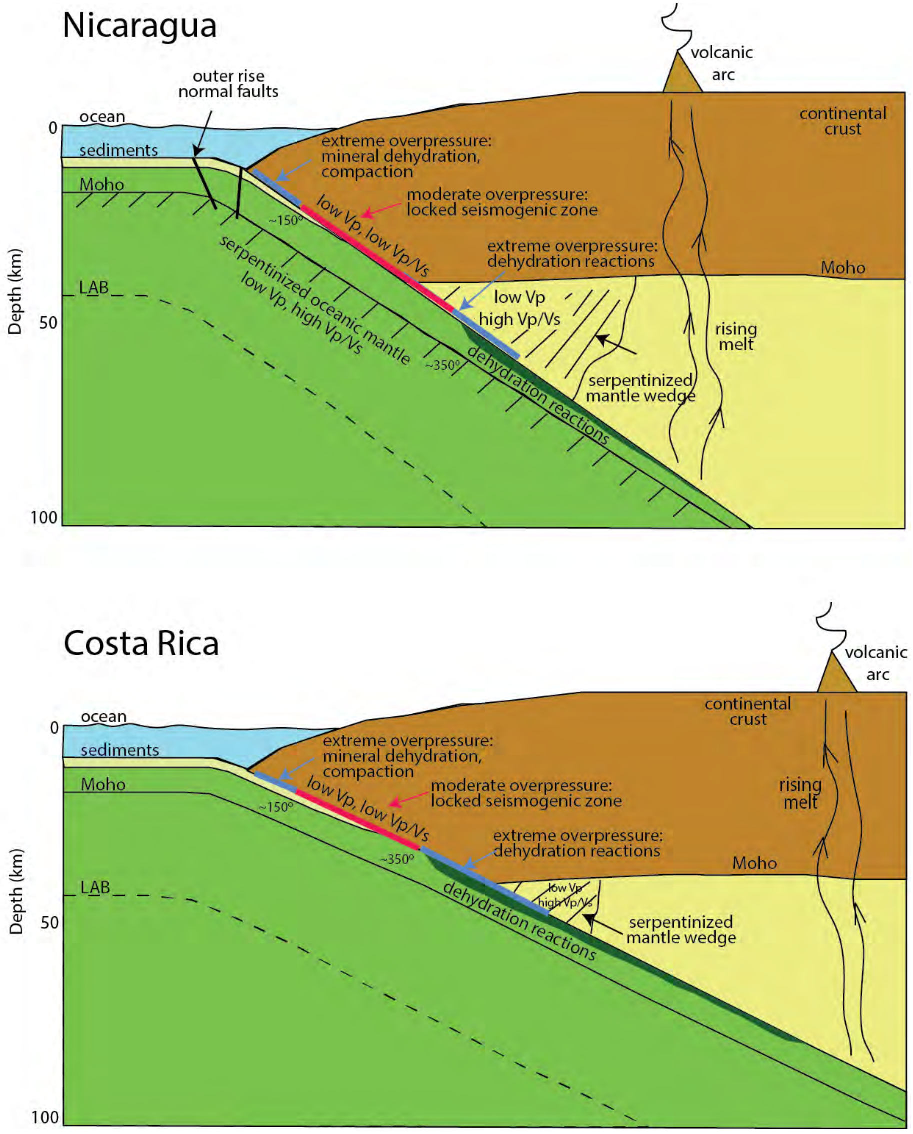
Thermal model provided by Rob Harris

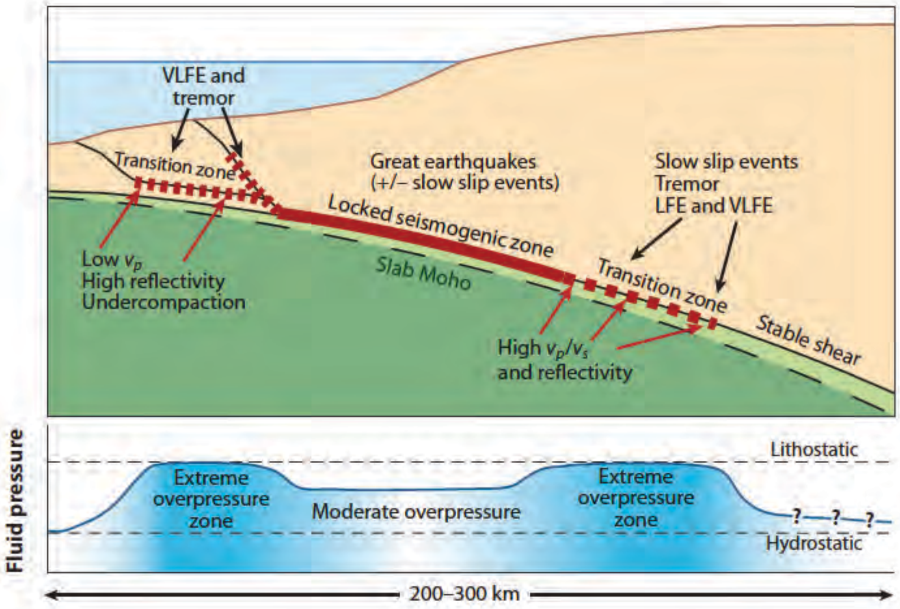


6. Seismogenic zone associated with low Vp along most of the Costa Rica and Nicaragua margin

Summary of Observations

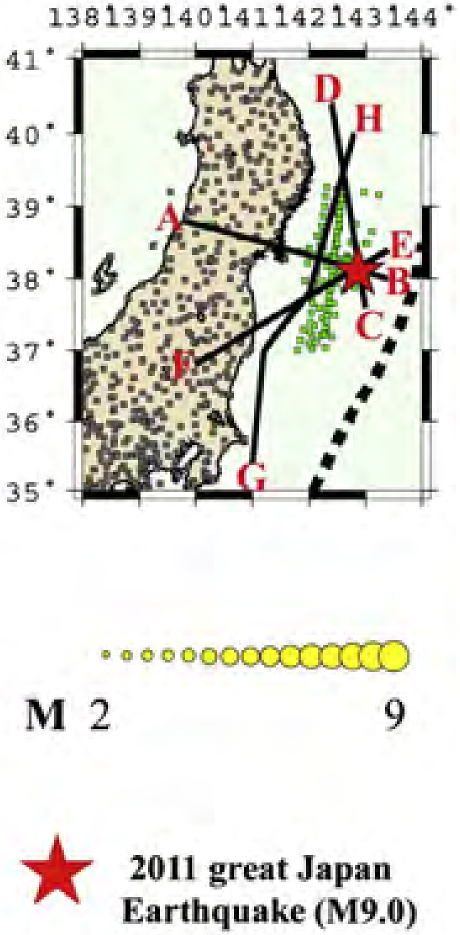
- The seismogenic zone is associated with a low Vp and low Vp/Vs anomaly along the plate interface.

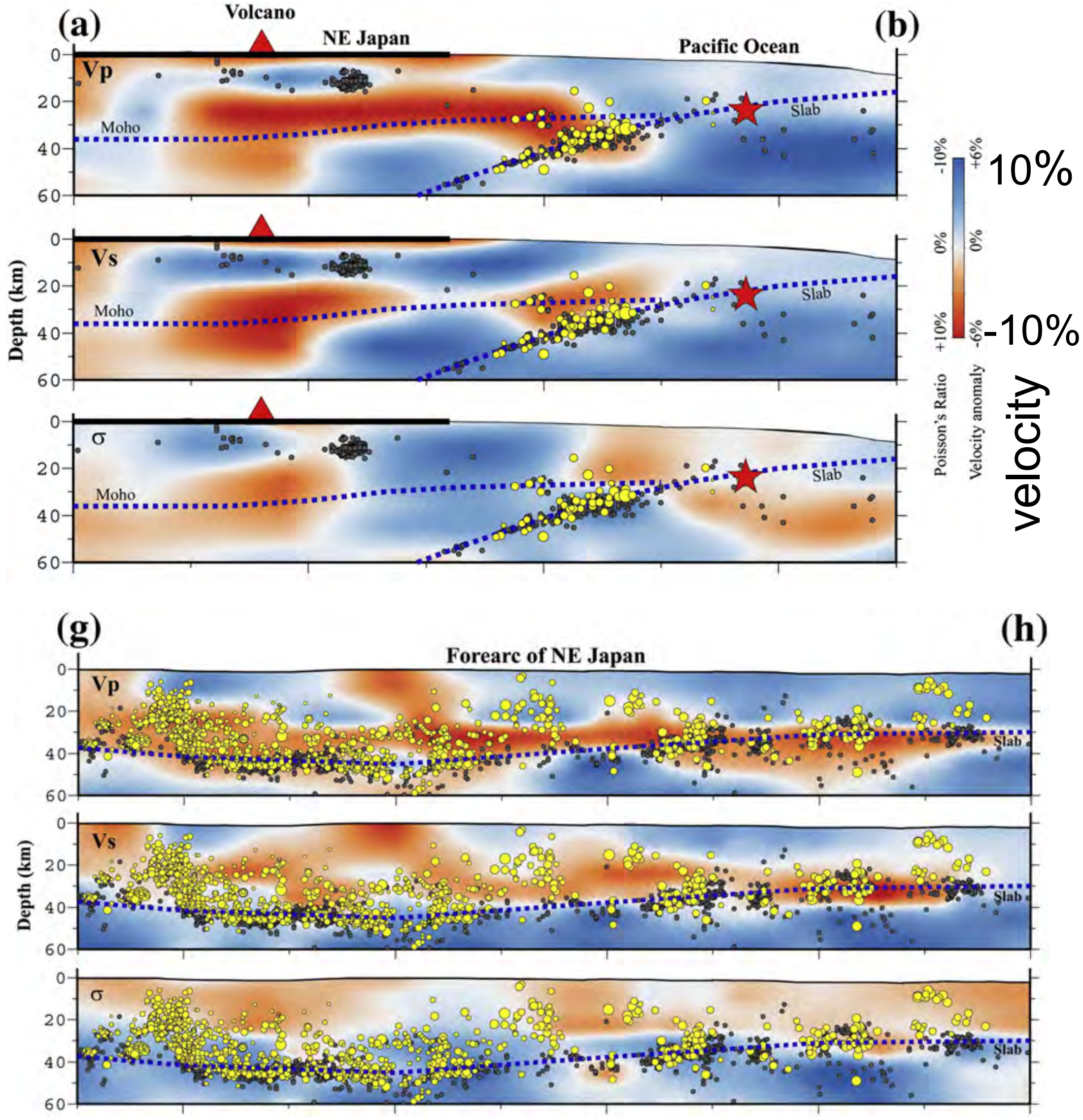




From Saffer & Tobin, 2011

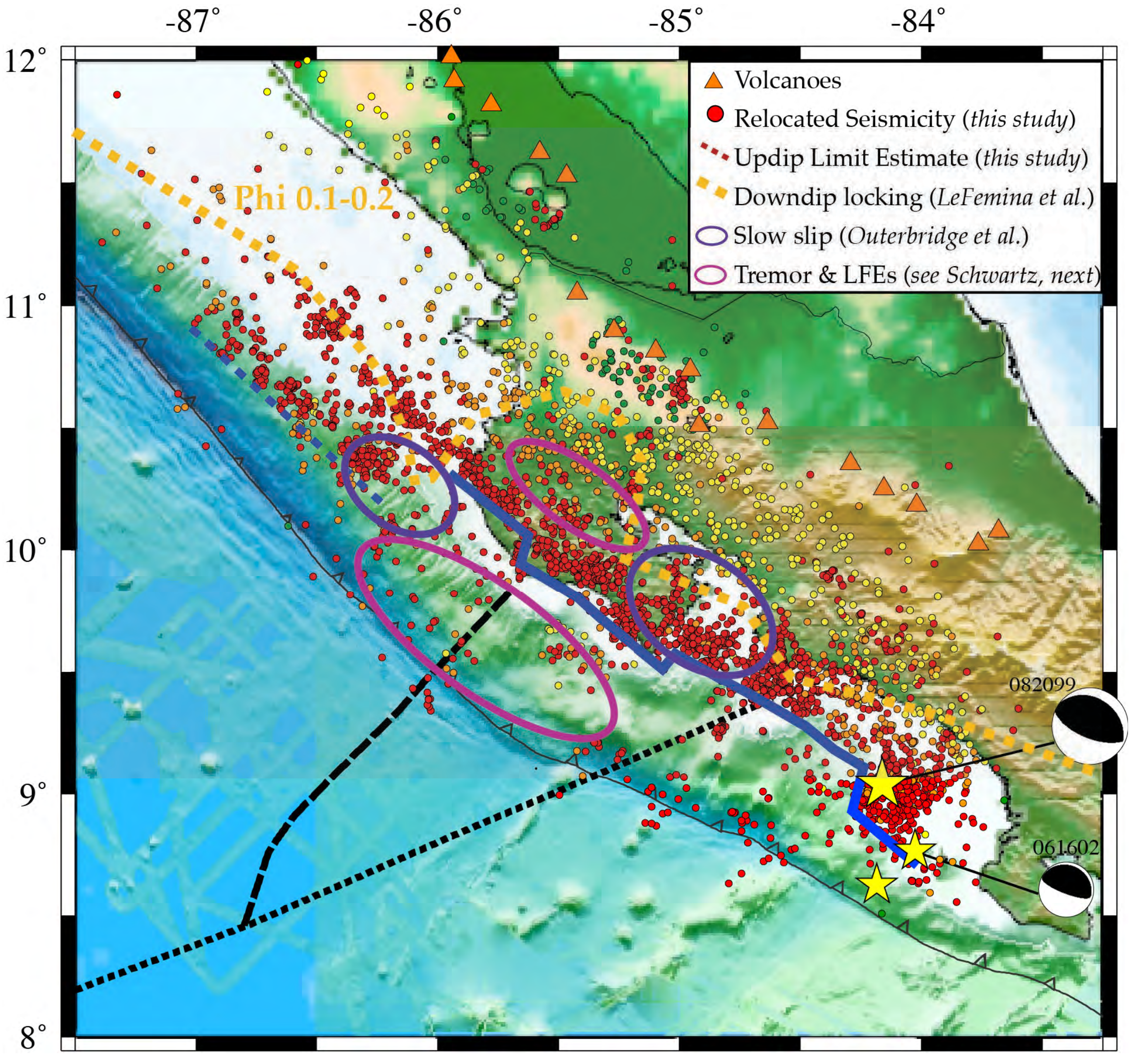
2011 great Japan earthquake



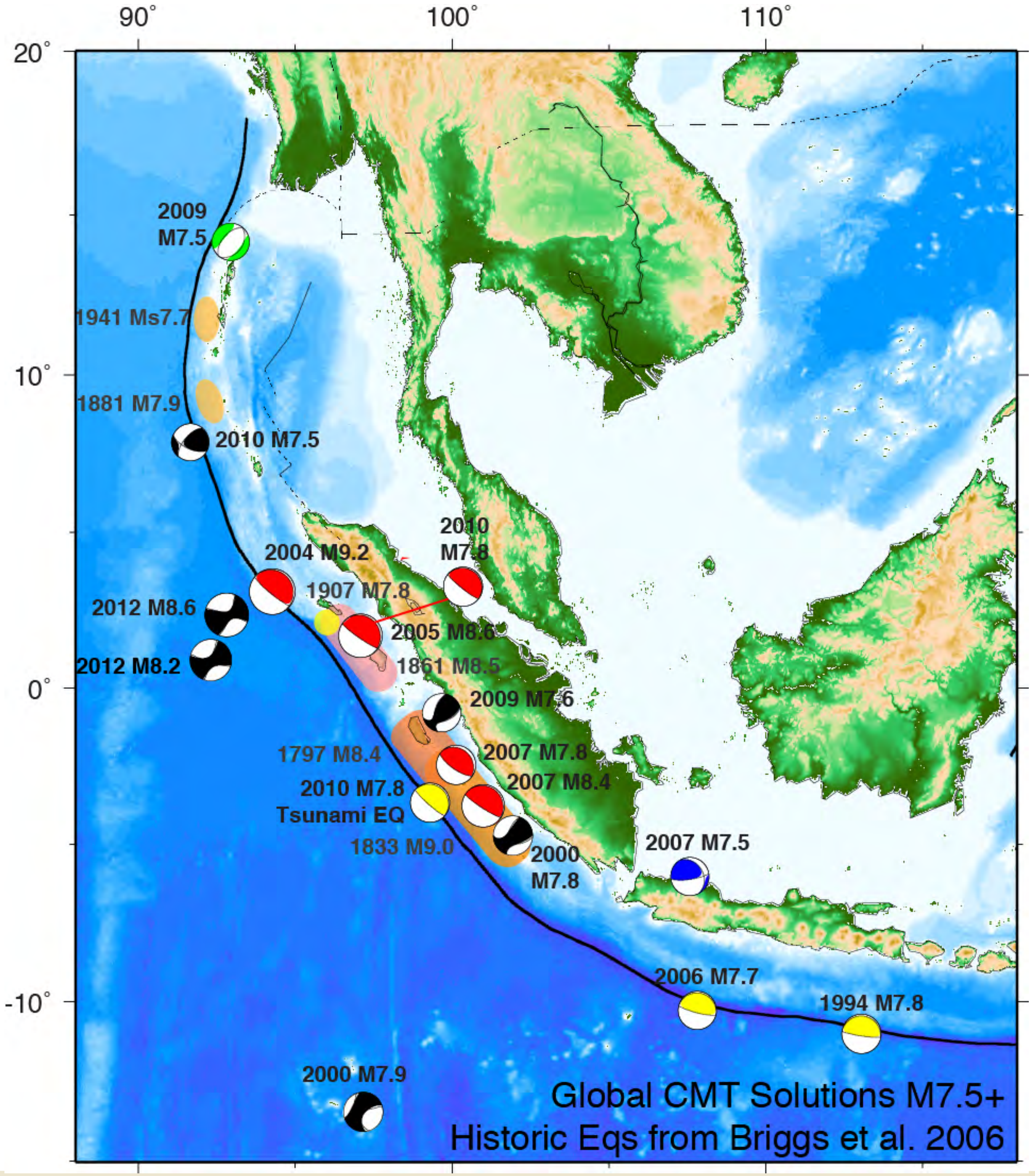


Wang et al., 2012

- Vp and Vp/Vs models indicate along strike changes in the state of hydration of the slab and the forearc mantle wedge.
- Vp and Vp/Vs models reflect down-dip changes in the degree of overpressure developed along the plate interface, which map into changes in slip behavior along the seismogenic zone.



Sunda Subduction Zone



Global CMT Solutions M7.5+
Historic Eqs from Briggs et al. 2006

Tomography Opportunity

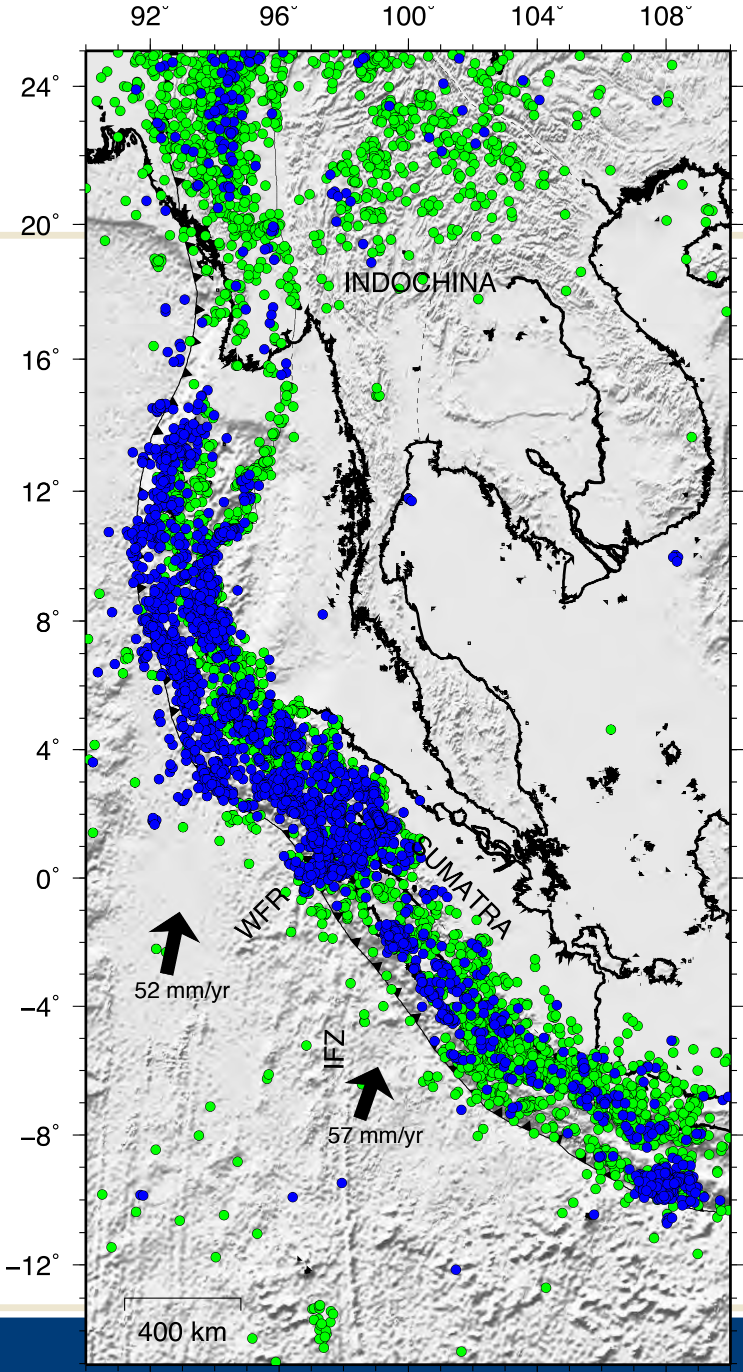
- Improved event distribution from aftershocks of the 2004 and 2005 great earthquakes

Before: **5,460 earthquakes**

- 94,529 seismic phases
- 1,706 stations

After: **3,372 earthquakes**

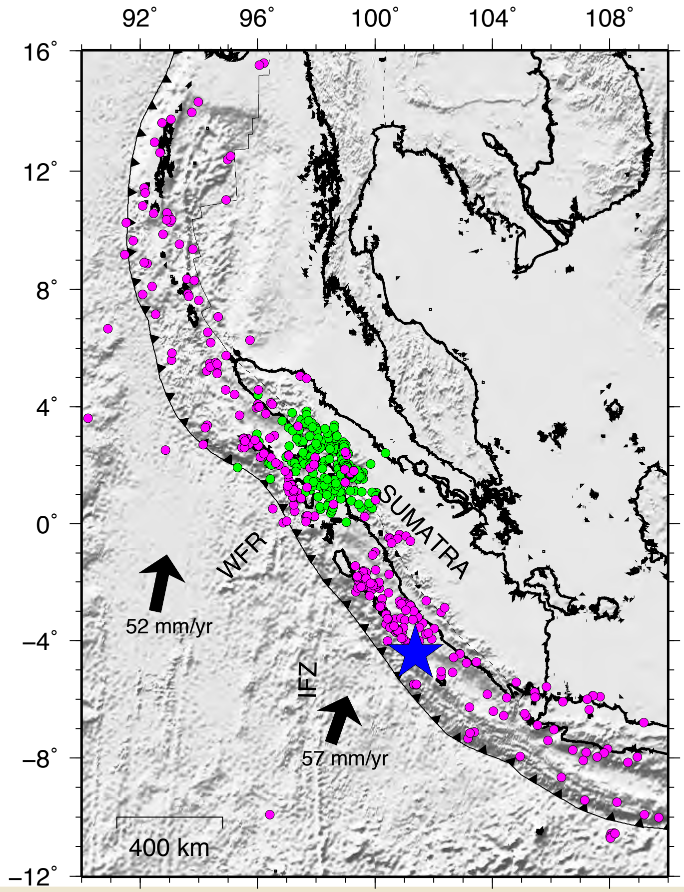
- 527,713 seismic phases
- 2,099 stations



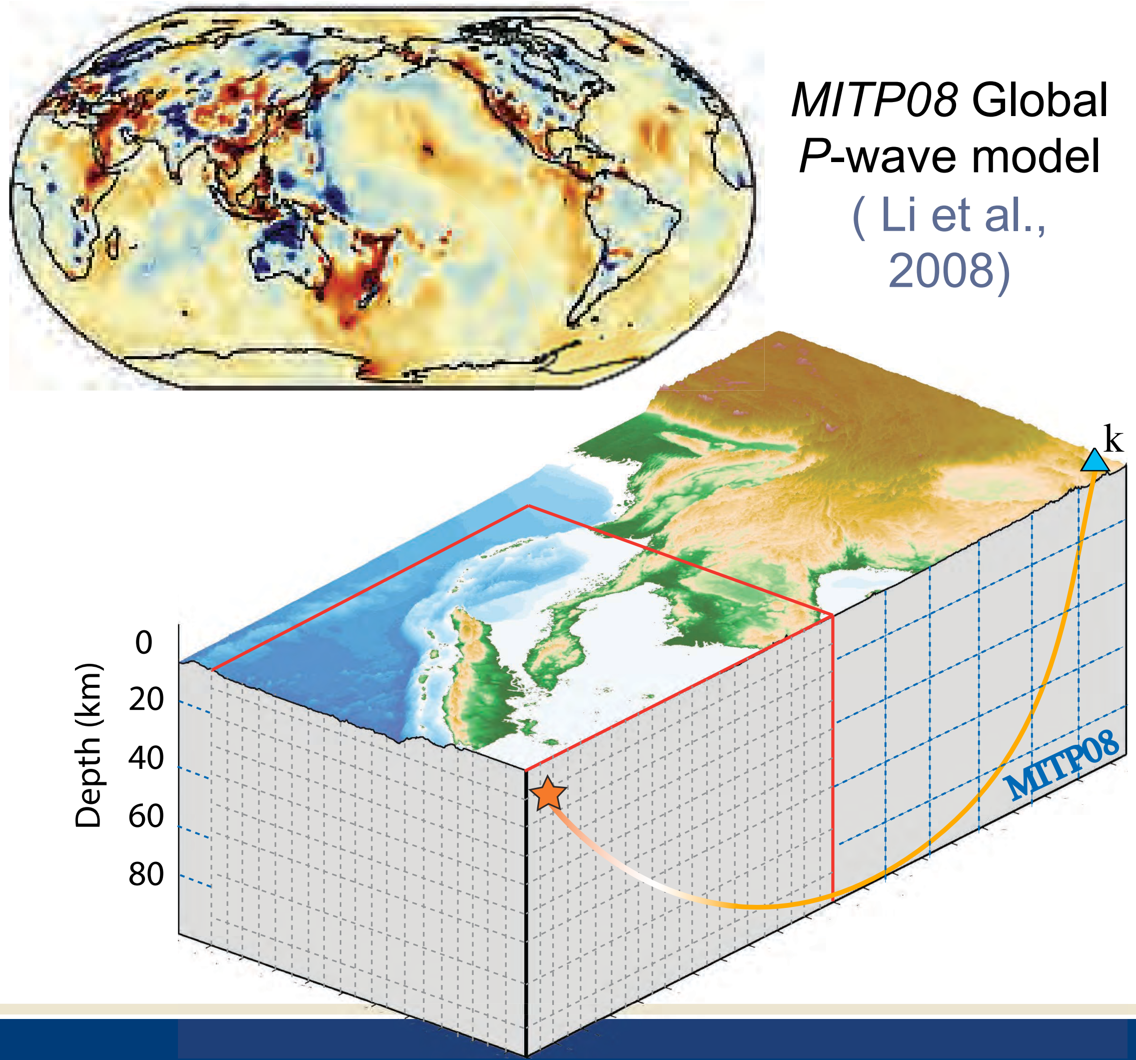
Improving a Nested Tomography Model

2007 Mw 8.5 and aftershocks

Local Toba Caldera Data



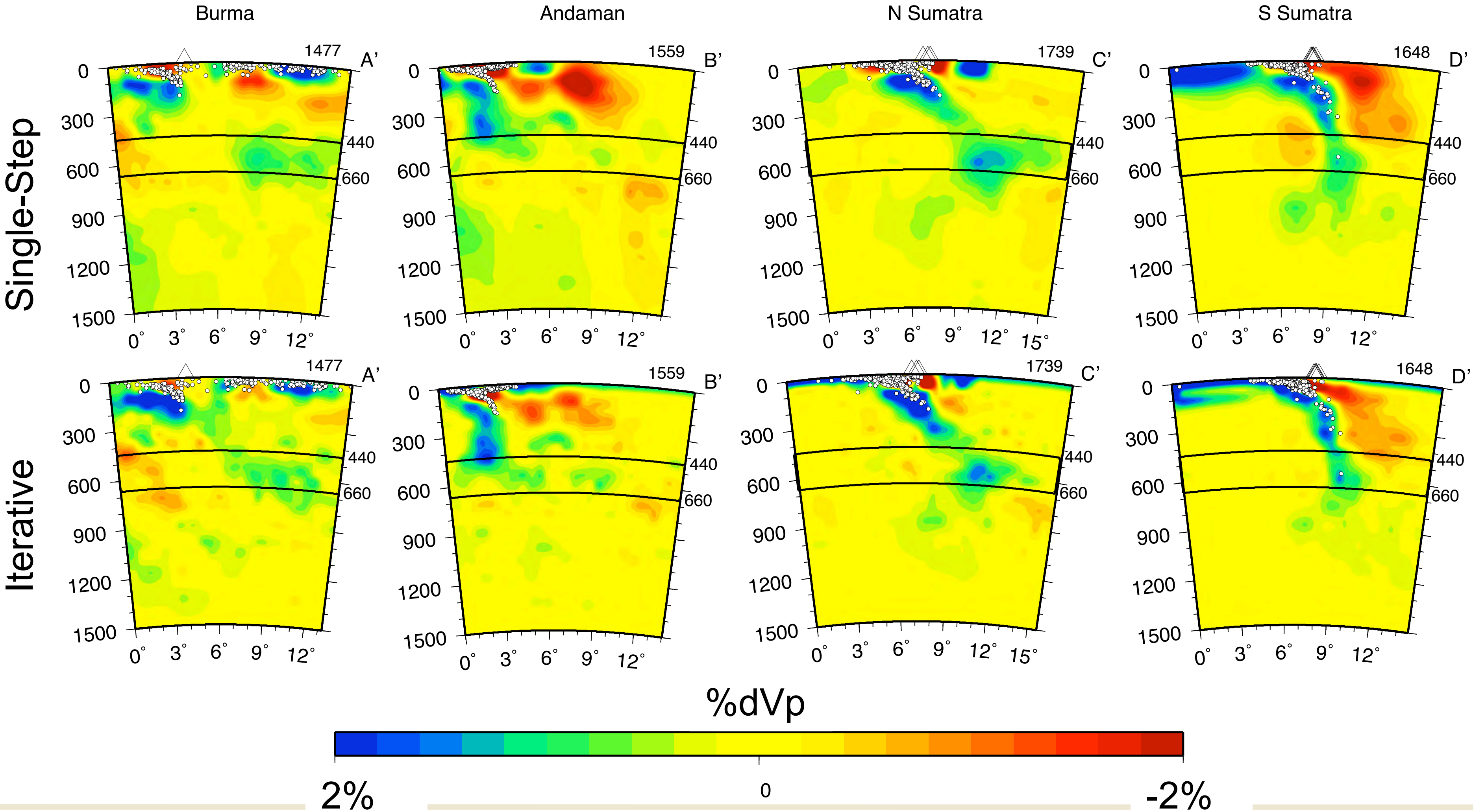
(1%; 150 km)



MITP08 Global *P*-wave model

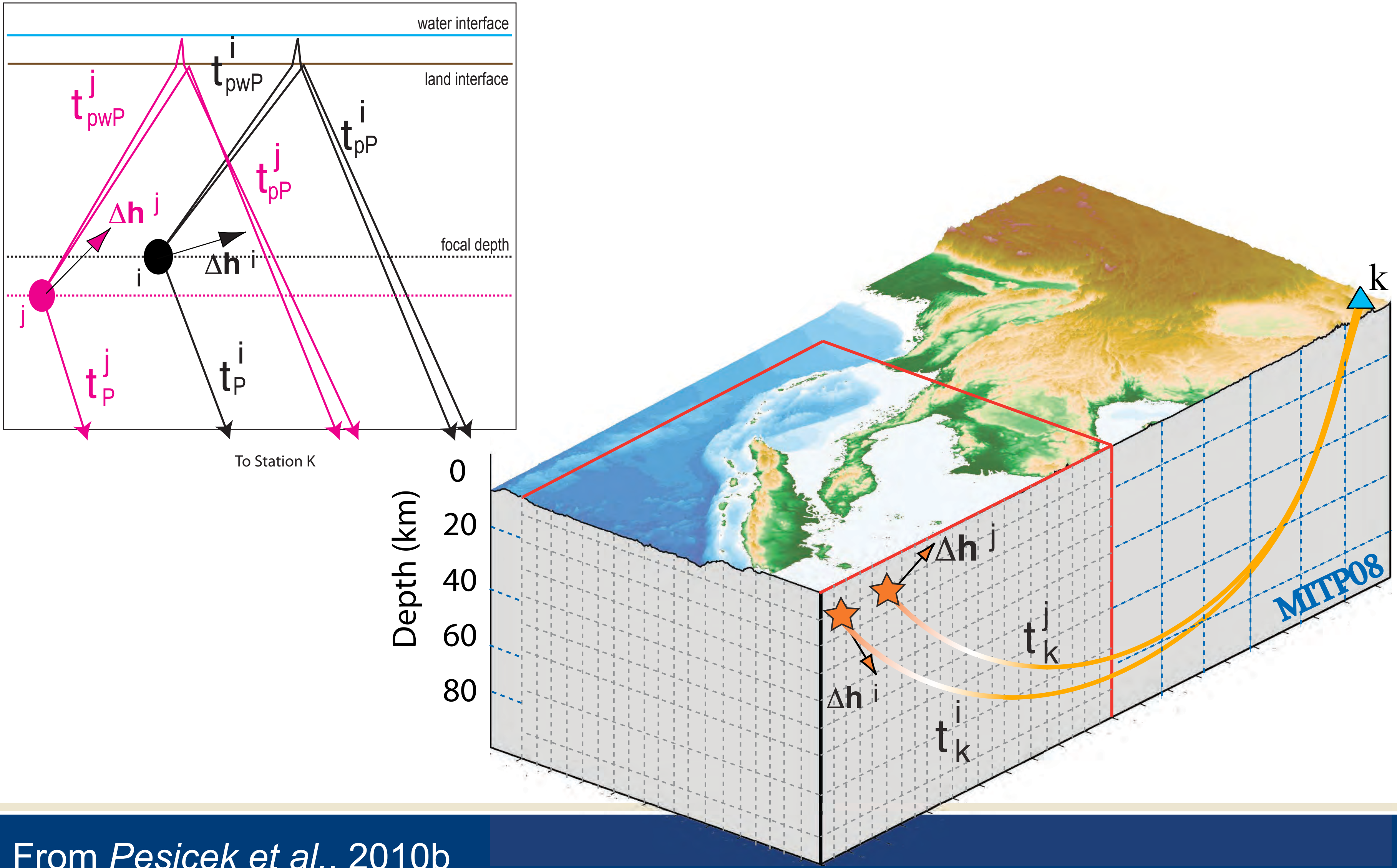
(Li et al., 2008)

Iterative Results



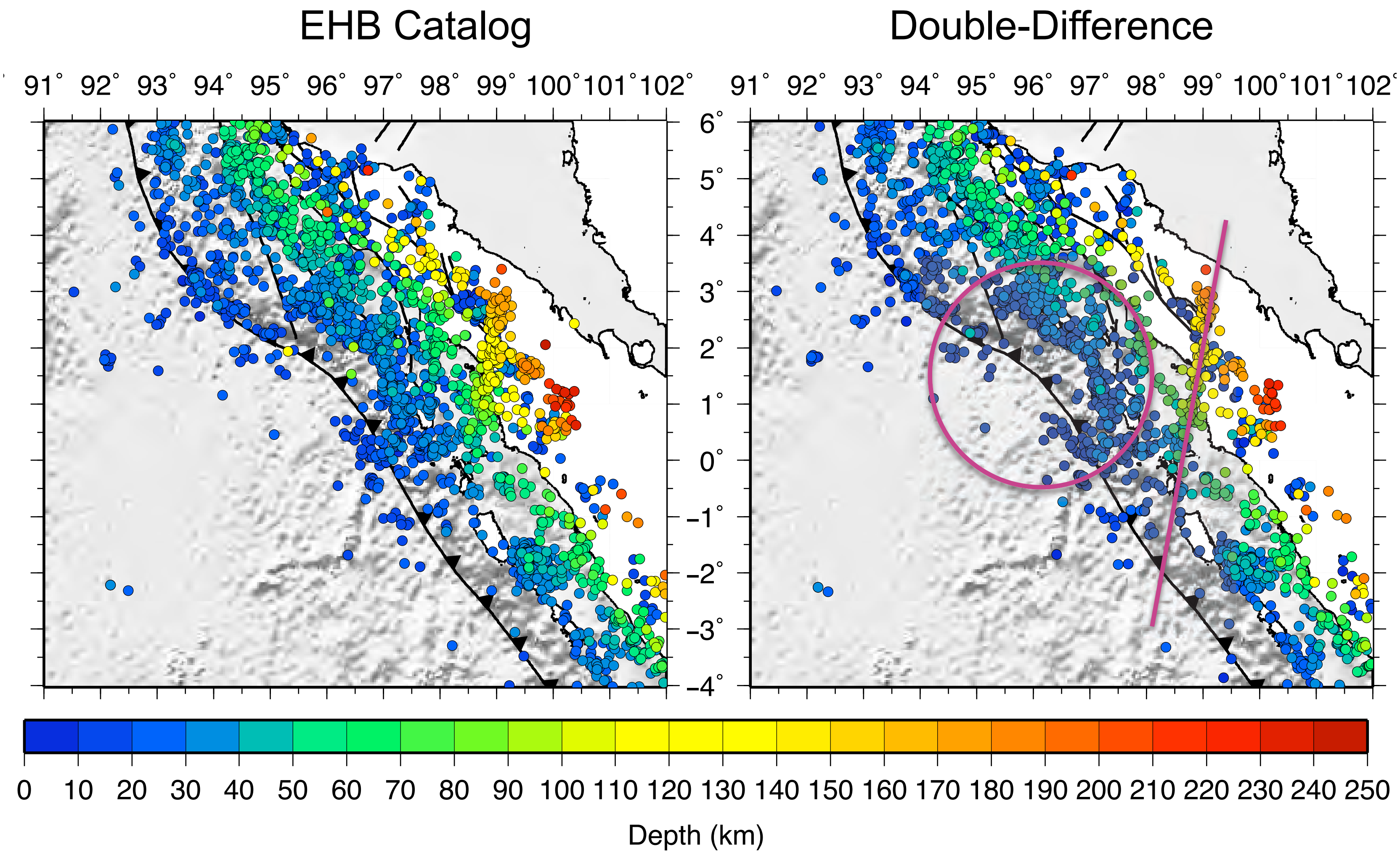
From *Pesicek et al.*, 2010a

Teleseismic DD Earthquake Relocation



From *Pesicek et al.*, 2010b

Map view location comparison

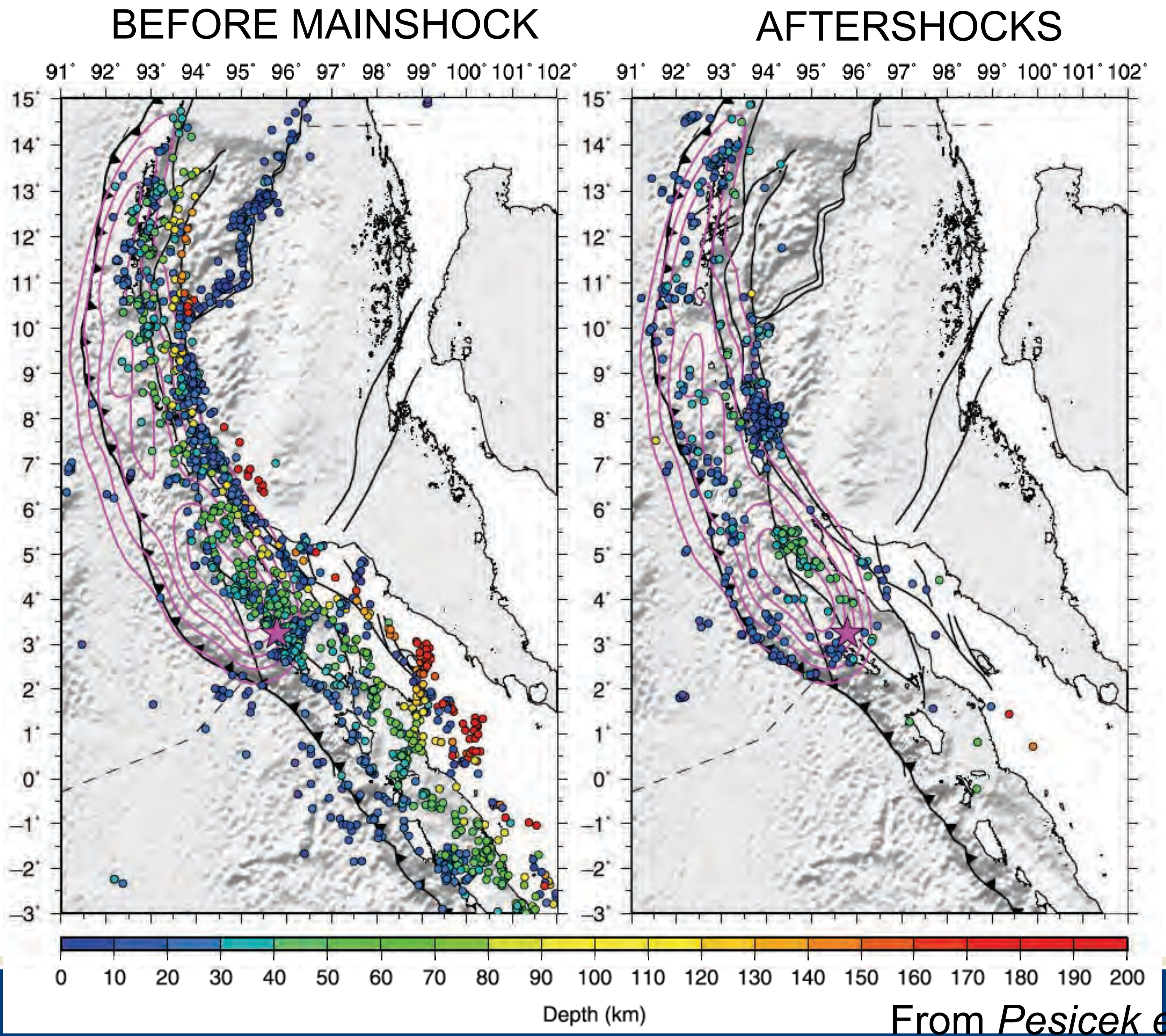


EHB Catalog

Double-Difference

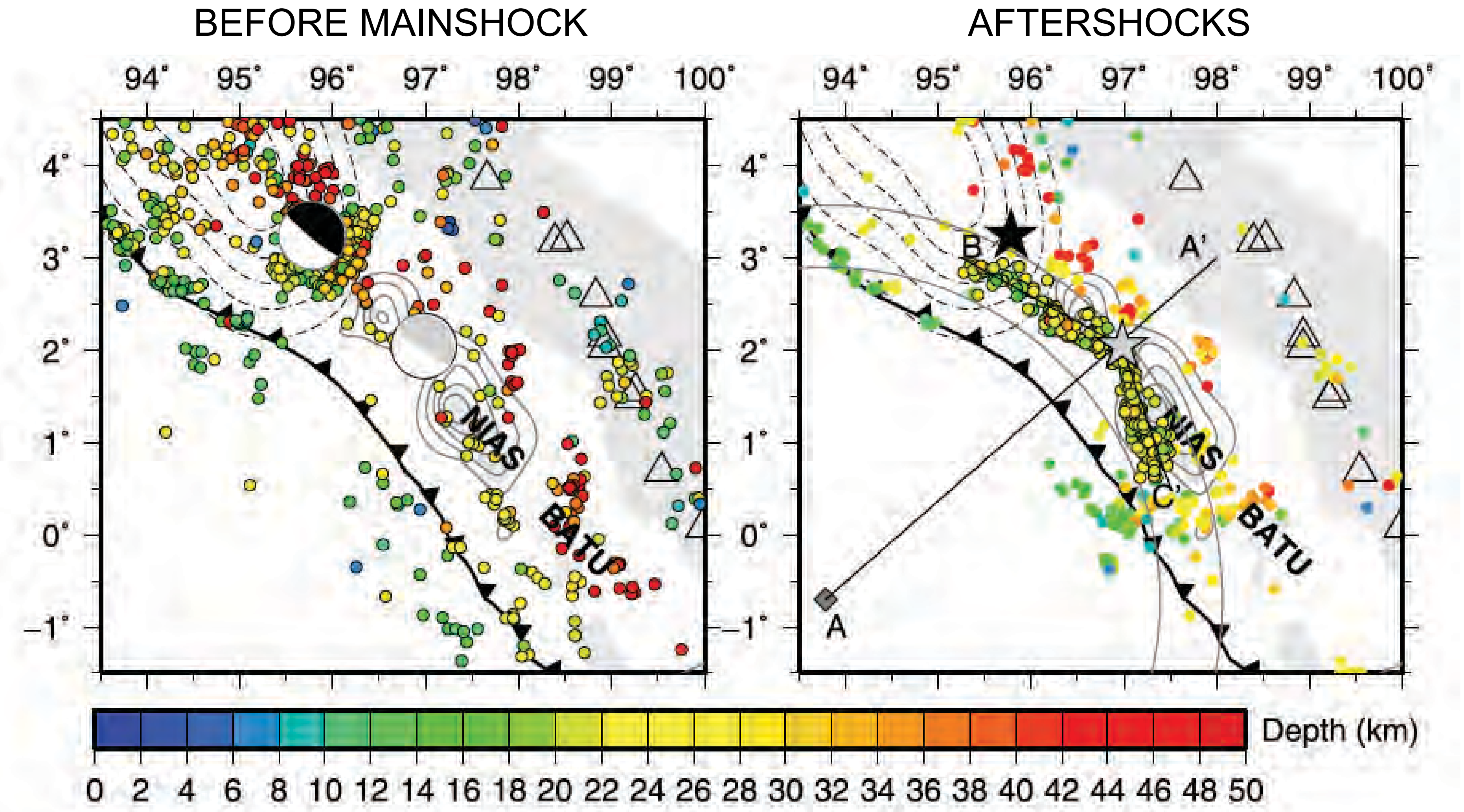
From *Pesicek et al.*, 2010b

2004 M9 Earthquake Coseismic Slip & Aftershocks



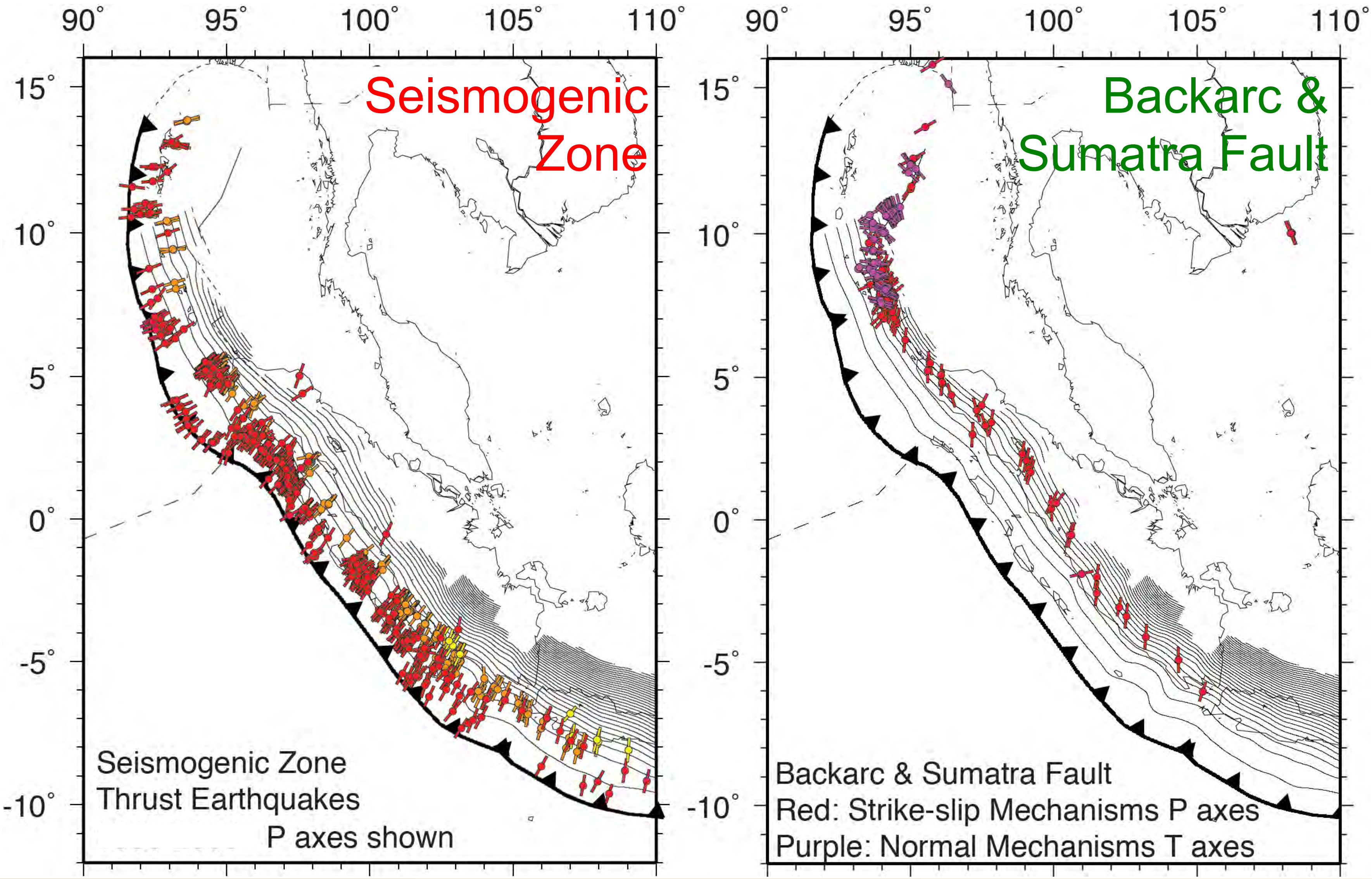
From *Pesicek et al.*, 2010b

2005 M8.7 Nias Coseismic Slip & Aftershocks

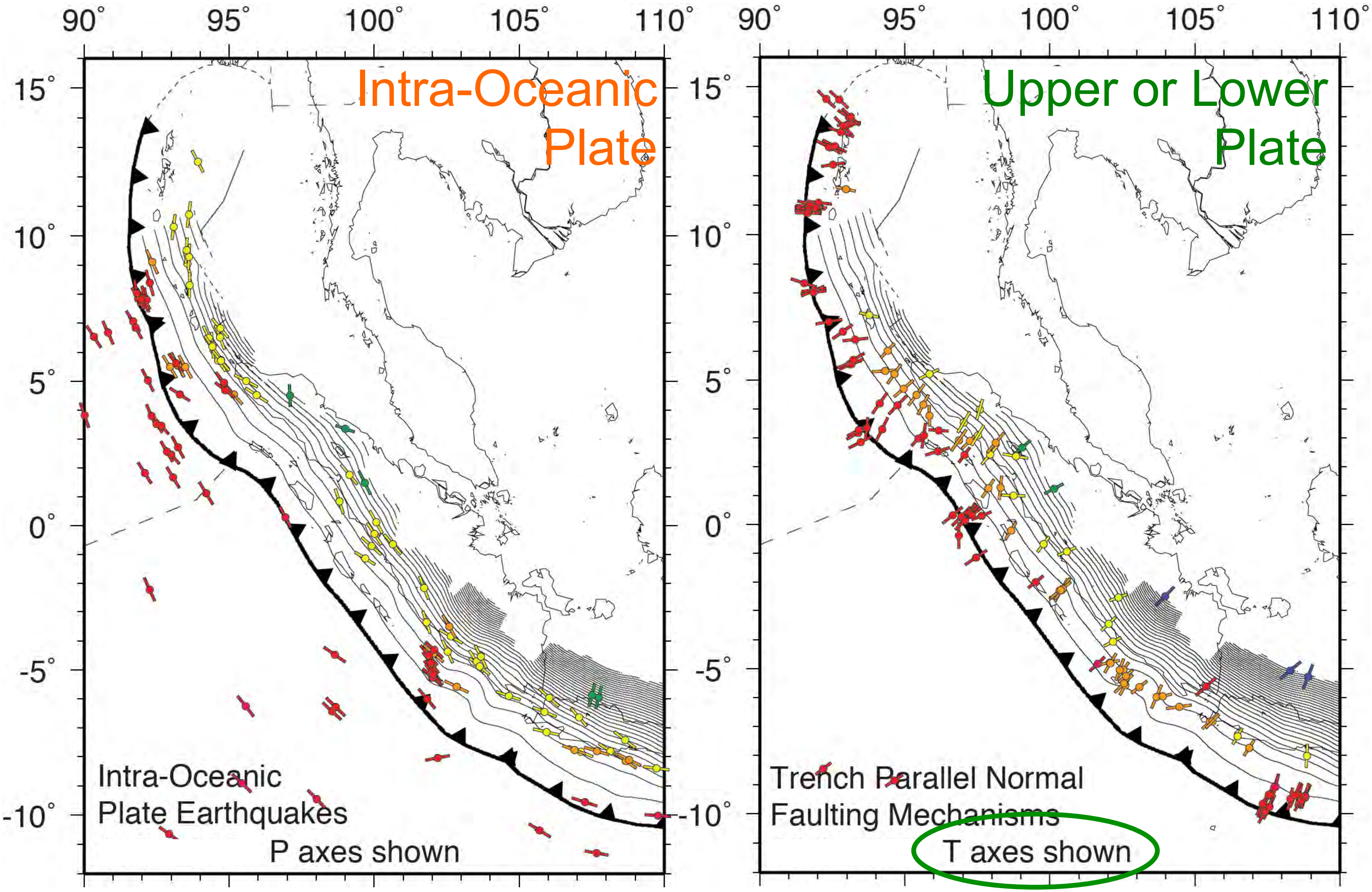


From *Pesicek et al.*, 2010b

CMT solutions through 2009 at the DD locations

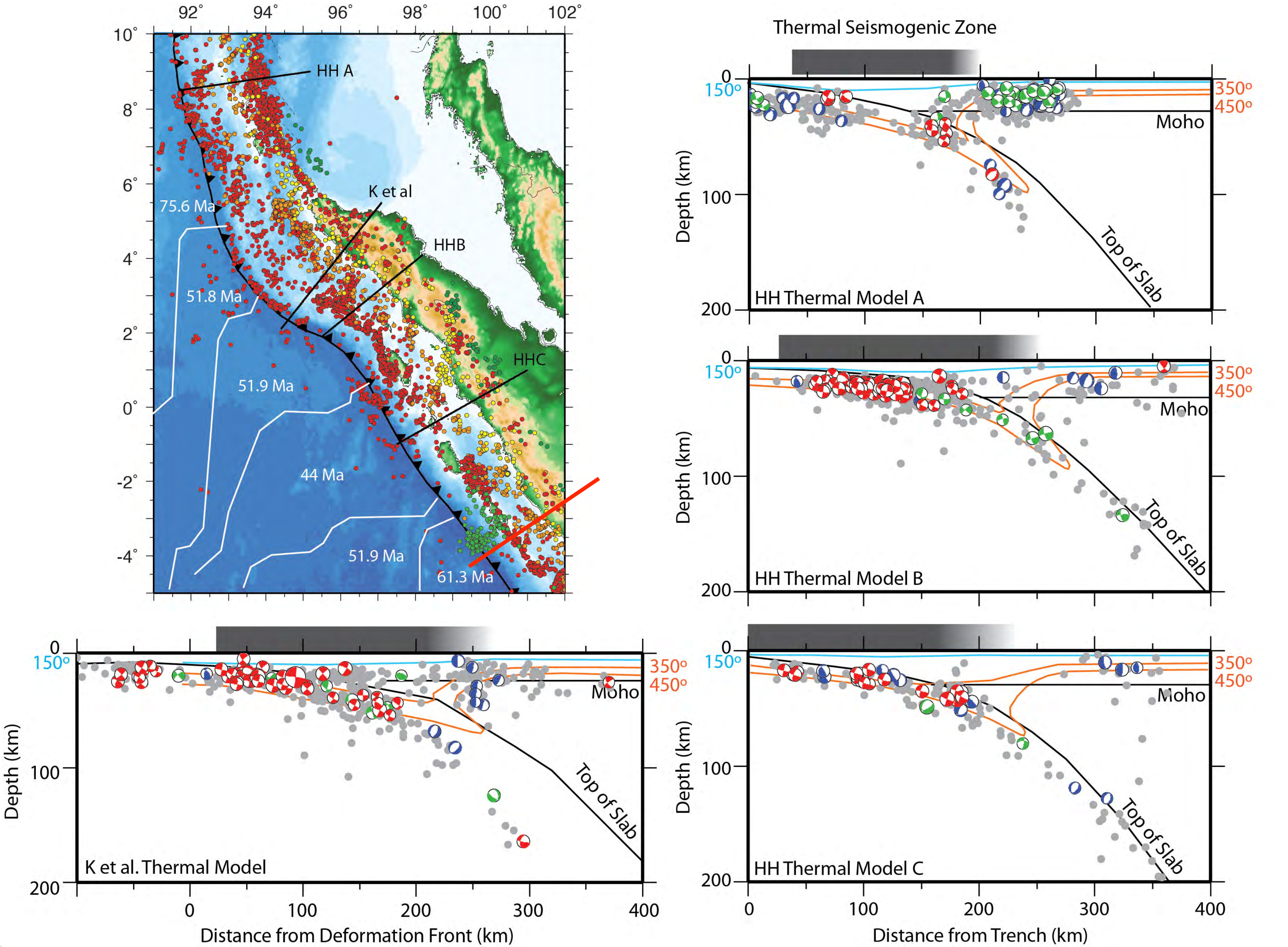


CMT solutions through 2009 at the DD locations



Intra-Oceanic Plate

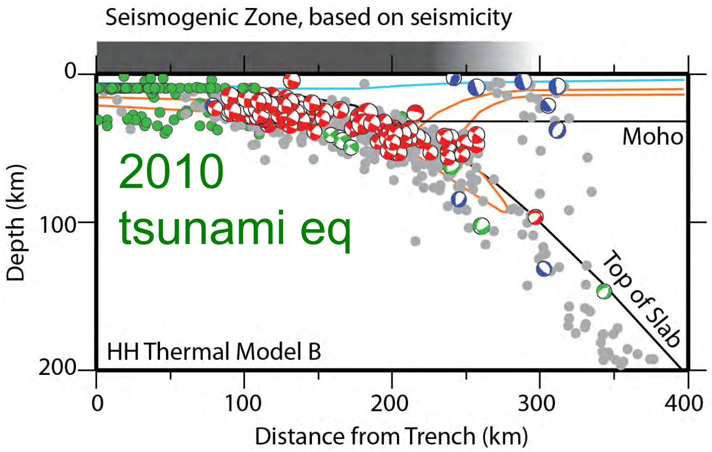
Upper or Lower Plate



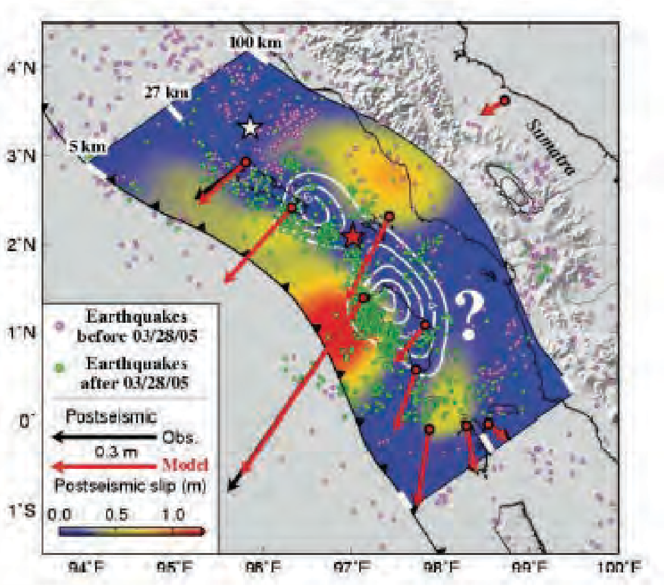
Thermal models from Hippechen and Hyndman, 2008; Klingelhoefer et al., 2010

Sunda Summary

- High-resolution DD relocations using teleseismic data reveal fine-scale spatial patterns of seismicity with the subduction zone



- Confirmed that megathrust seismicity occurs downdip of the Moho/slab intersection and is more consistent with thermal proxies in this region



- The potential for slip to the trench cannot be discounted along ALL of the margin

From Hsu et al., 2006

Final Thoughts

- Continued improvements in teleseismic location accuracy will allow more thorough global studies of seismogenic zone processes

- Local data is necessary for detailed seismic images of the subduction boundary and thorough integration with other geophysical datasets

- Plethora of great megathrust earthquakes since 2004 have potentially illuminated a broad range of subduction zone ‘types’ and could be studied using teleseismic data

How YOU Can Participate in GeoPRISMS

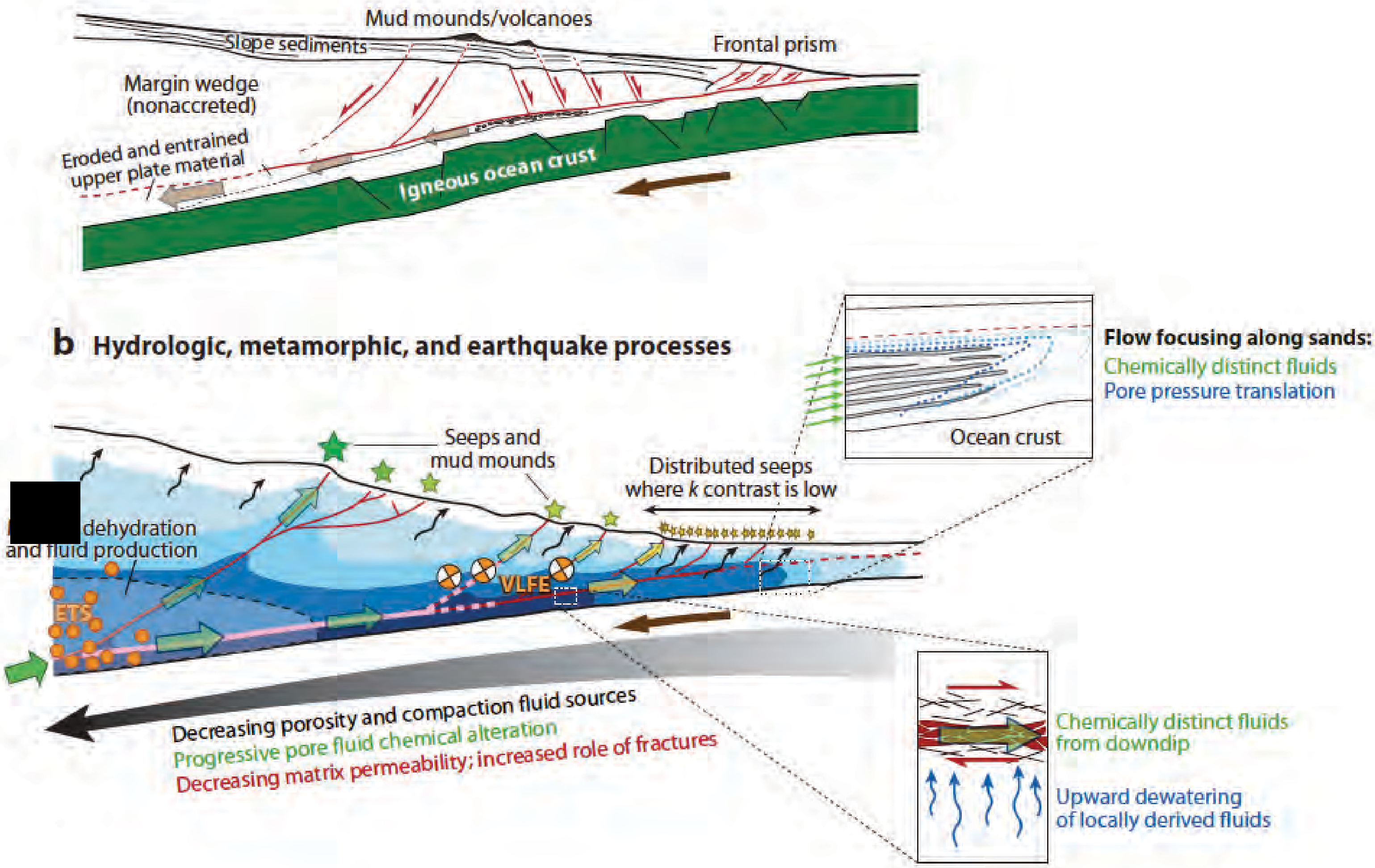
- Attend upcoming workshops, AGU mini-workshops
- Participate in on-line discussions & forum
- Communicate with conveners & GSOC members
- Sign up for listserv and newsletters
- Browse the MARGINS and GeoPRISMS databases, bibliographies, reports
- Test out and contribute MARGINS mini-lessons
- Follow us on

  info@geoprisms.org
  www.geoprisms.org

Connect with us online

facebook.com/geoprisms twitter.com/geoprisms

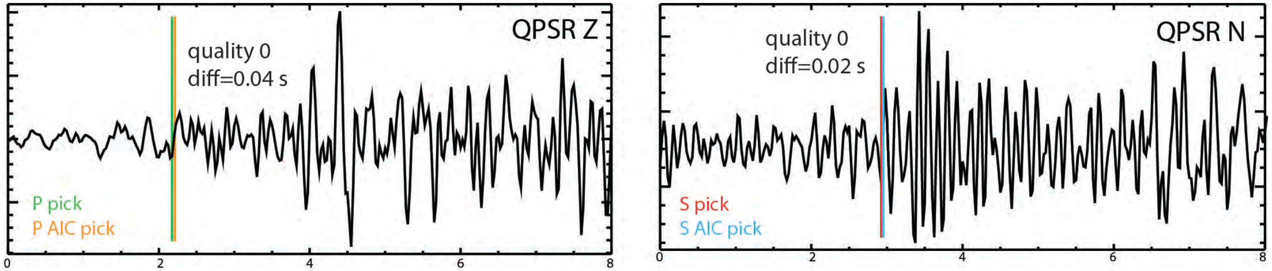
- Do GREAT Science!! Send Us Reports, Images, etc.



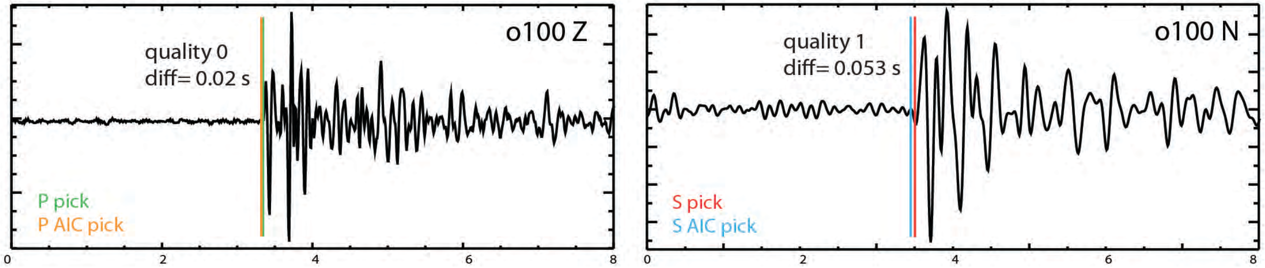
From Saffer & Tobin, 2011

- Integrated data and defined a consistent weighting scheme

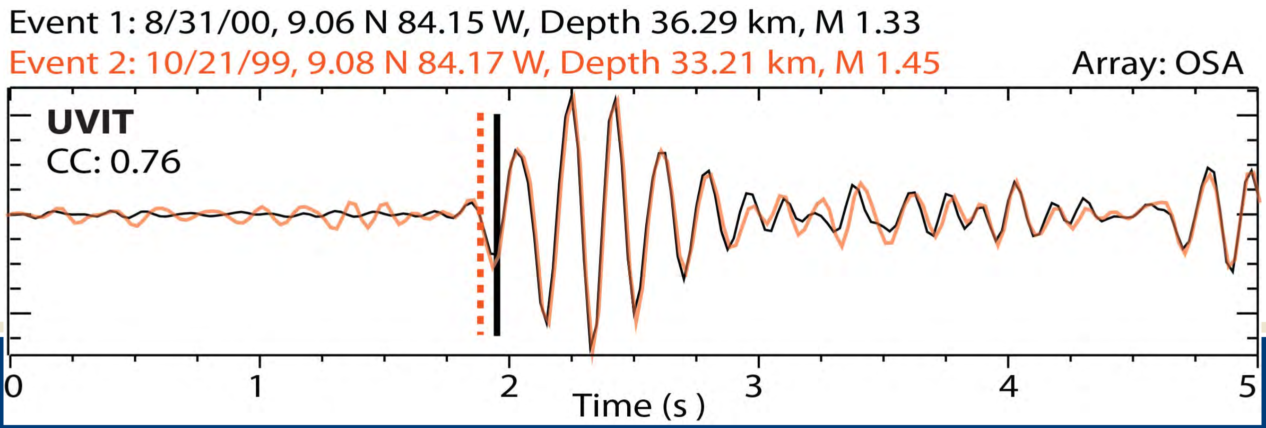
Osa



Nicat



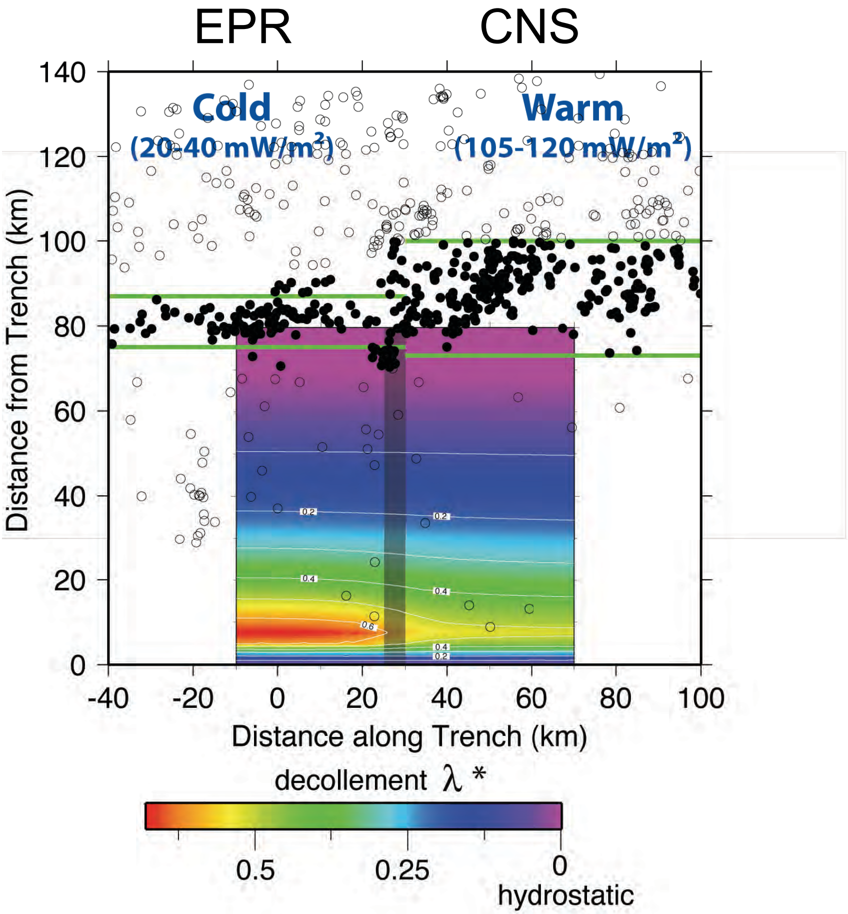
- Cross-correlated waveforms for accurate differential times


Event 1: 8/31/00, 9.06 N 84.15 W, Depth 36.29 km, M 1.33

Event 2: 10/21/99, 9.08 N 84.17 W, Depth 33.21 km, M 1.45

Array: OSA

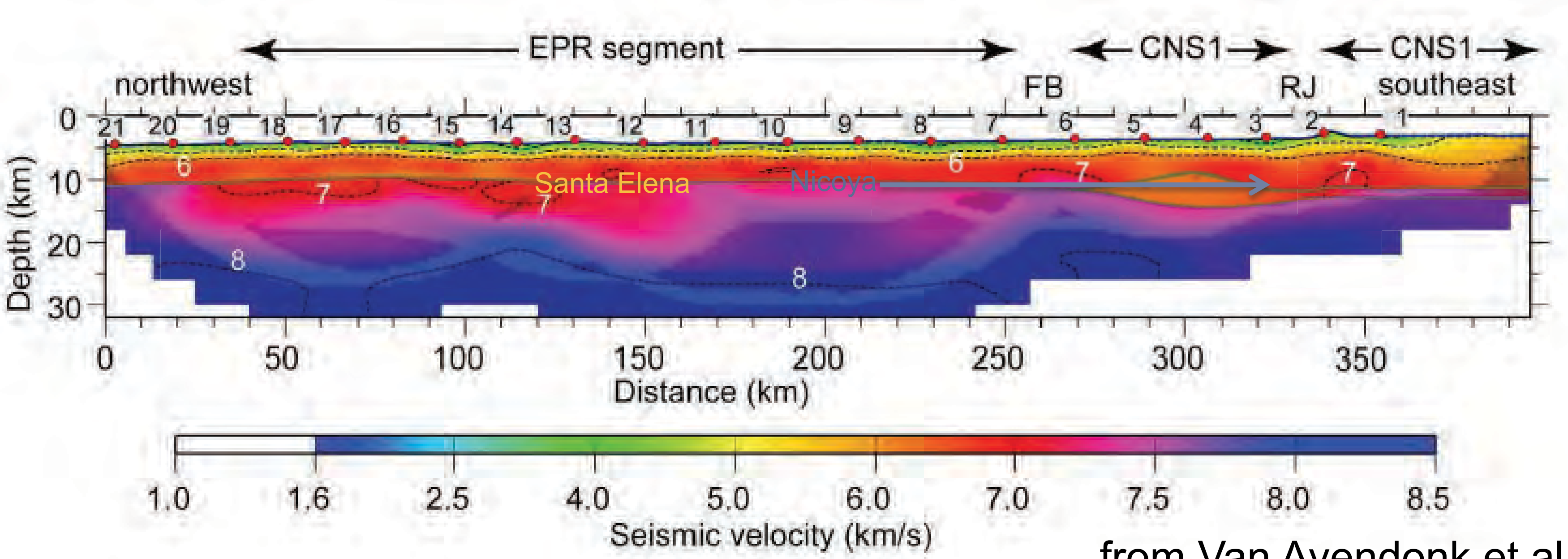
- Changes in temperature and/or pore fluid pressure along-strike spatially correlate with changes to the updip limit of seismogenic zone microseismicity.



Data from Spinelli and Saffer, 2007; DeShon et al., 2006; Fisher et al., 2003

Questions of Interest

- How do broad-scale changes in hydration state of the oceanic lithosphere affect shallow & intermediate depth intraslab earthquake occurrence?



from Van Avendonk et al. 2011

- How does forearc mantle wedge hydration change along-strike and does it exert a primary control on the down-dip limit of the seismogenic zone?

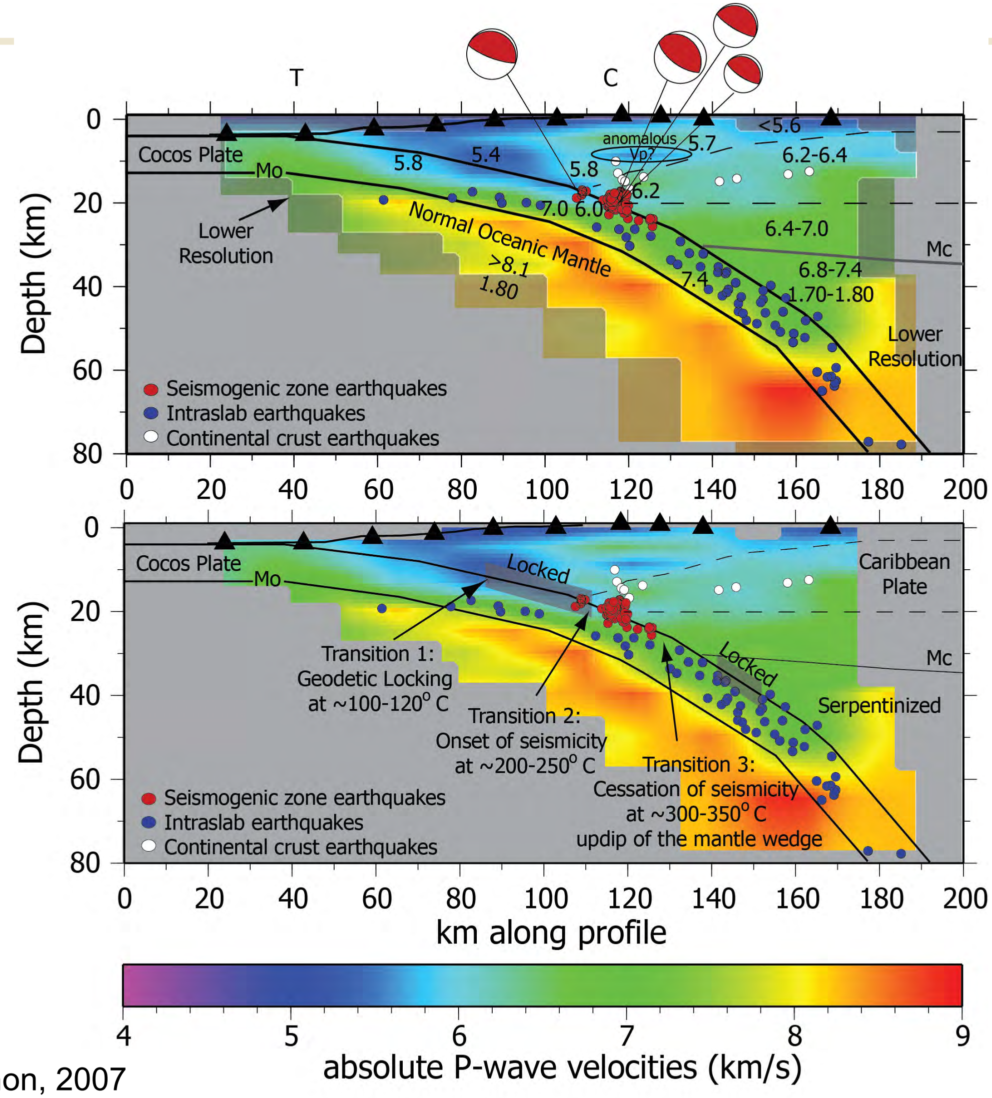
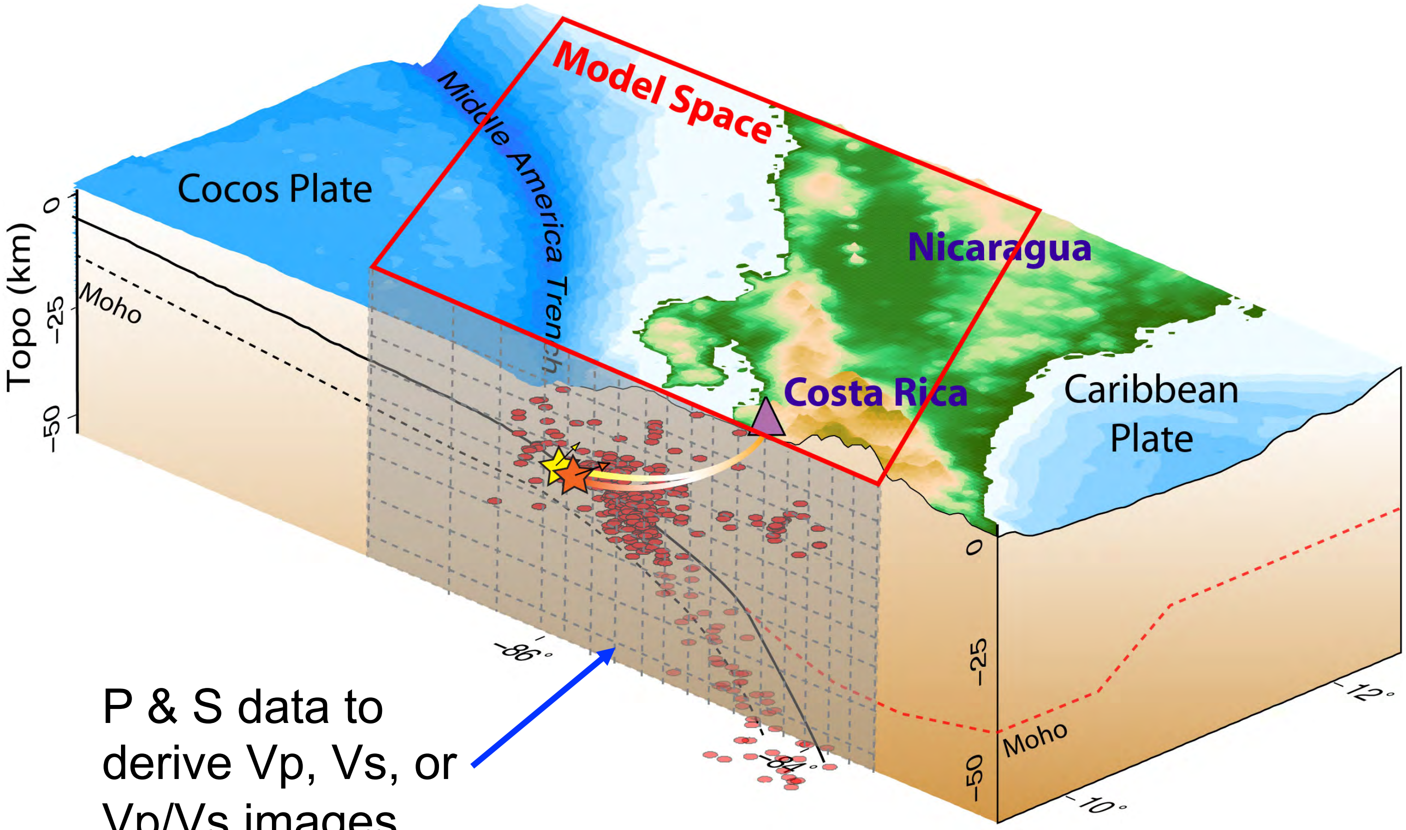


Image modified from DeShon et al. 2006; Schwartz and DeShon, 2007

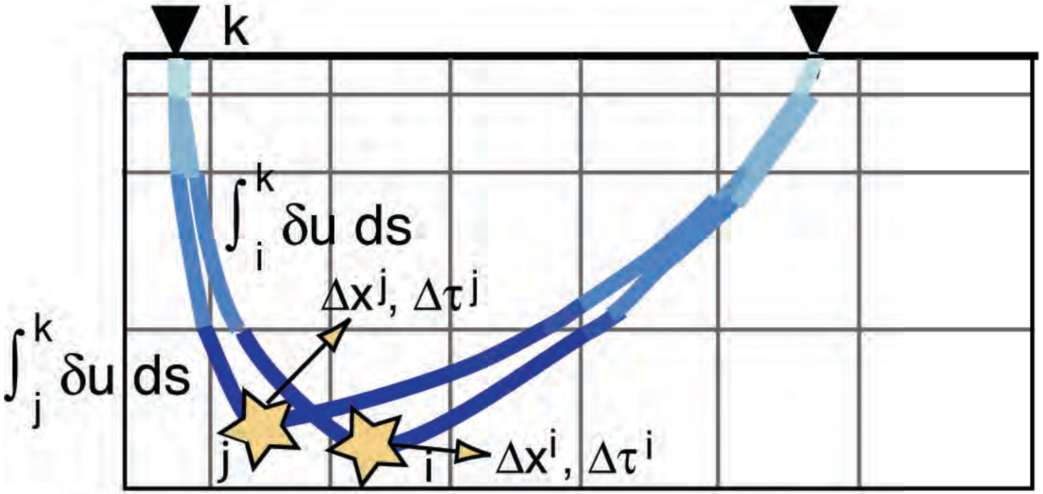
Double-Difference Tomography



P & S data to derive Vp, Vs, or Vp/Vs images

Absolute times, differential times, and waveform cross-correlation differential times

Double-difference tomography

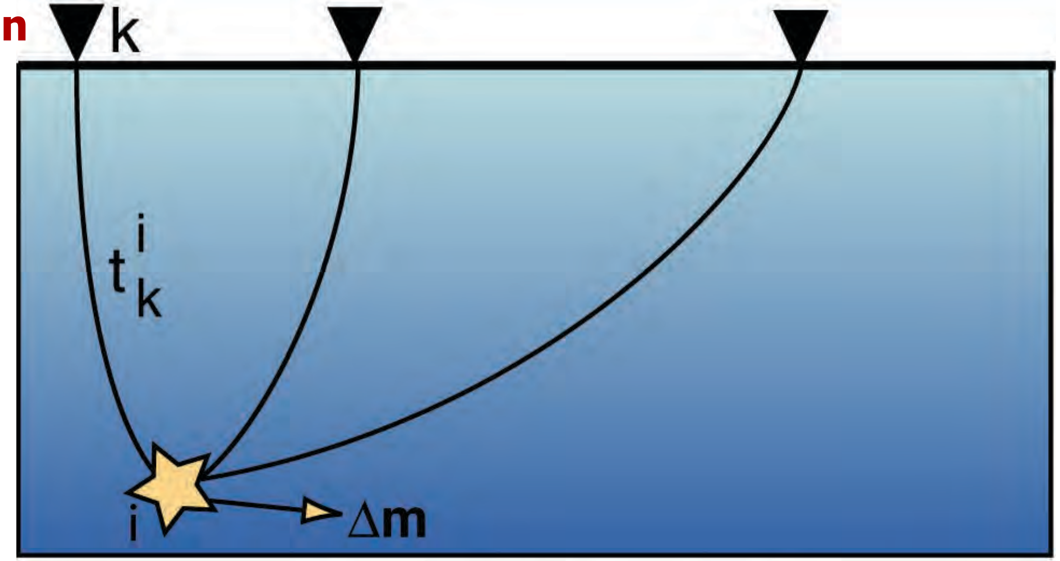


$$dr_k^{ij} = \sum_{l=1}^{3} \frac{\partial t_k^i}{\partial m_l^i}\Delta m_l^i + \Delta\tau^i + \int_i^k \delta u\, ds - \sum_{l=1}^{3} \frac{\partial t_k^j}{\partial m_l^j}\Delta m_l^j - \Delta\tau^j - \int_j^k \delta u\, ds$$

Zhang and Thurber, 2003

Earthquake location

station location



***A priori* velocity structure**

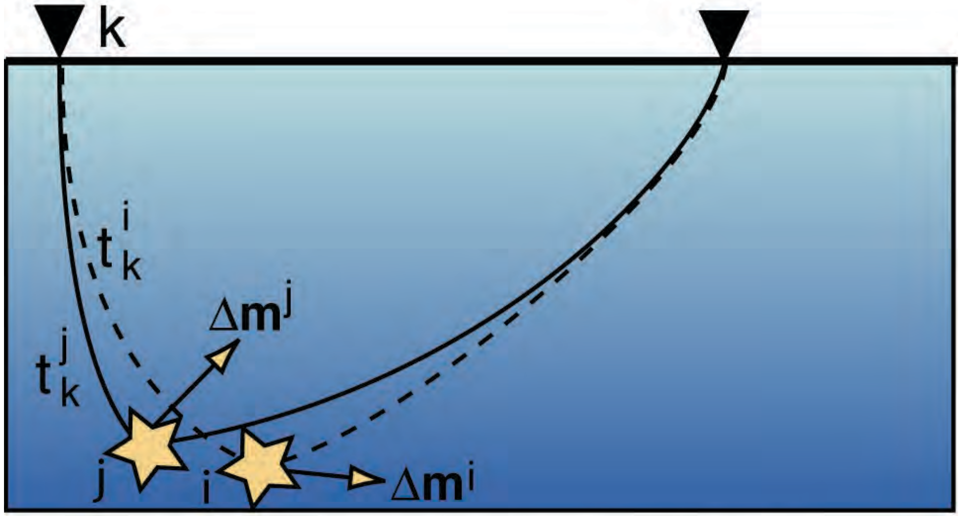
hypocentral parameters (origin time, latitude, longitude, depth)

$$dr^i_k = t^{i\,obs}_k - t^{i\,cal}_k$$

$$dr^i_k = \frac{\partial t^i_k}{\partial m}\Delta m^i$$

Inverse Problem

Double-difference Location



A priori
1D velocity
structure

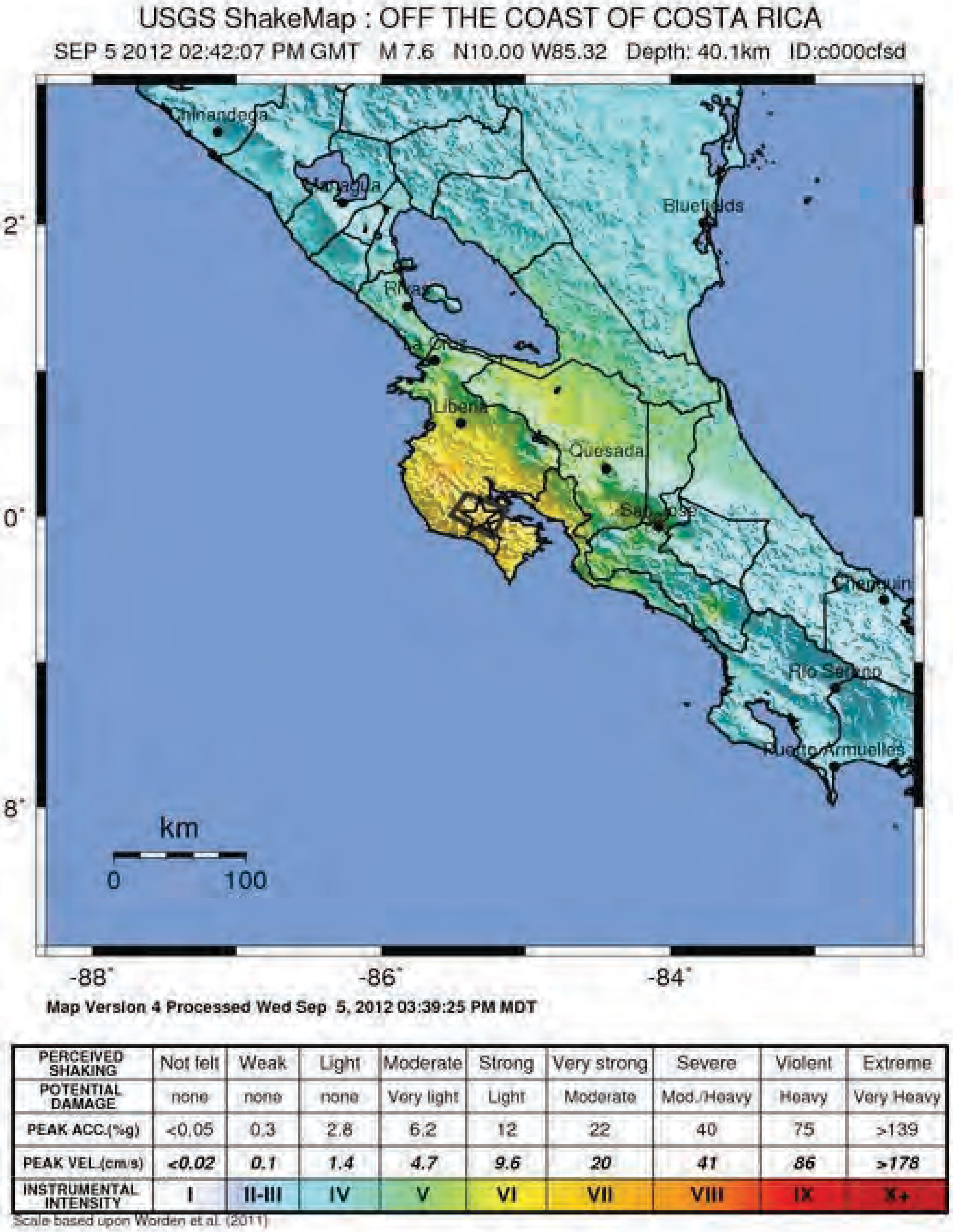
$$dr_k^{ij} = (t_k^j - t_k^i)^{obs} - (t_k^j - t_k^i)^{cal}$$

$$dr_k^{ij} = \frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^j}{\partial m}\Delta m^j$$

Waldhauser et al., 1999

Mw 7.6 Nicoya Earthquake

9/5/2012



USGS ShakeMap : OFF THE COAST OF COSTA RICA

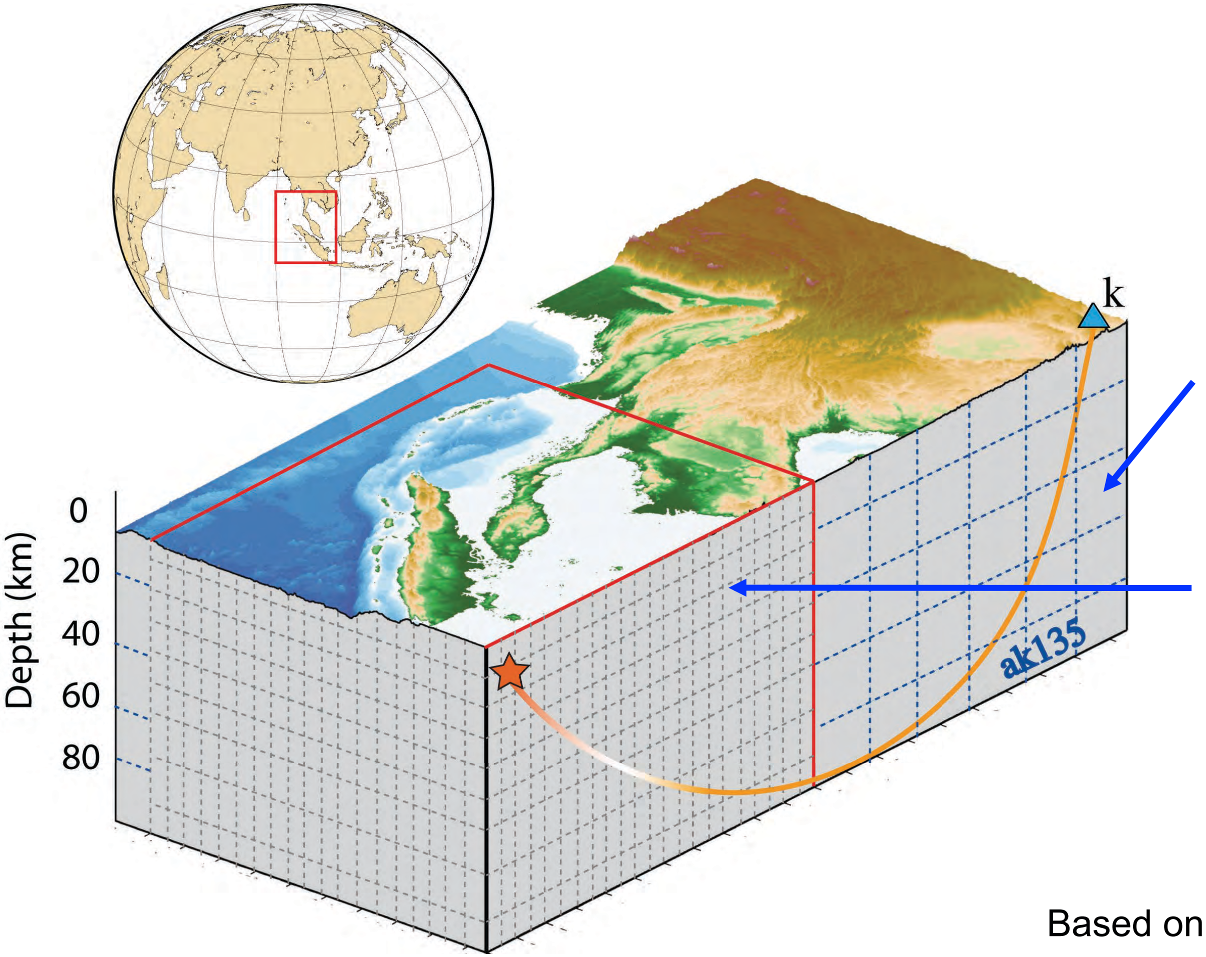
SEP 5 2012 02:42:07 PM GMT M 7.6 N10.00 W85.32 Depth: 40.1km ID:c000cfsd

Map Version 4 Processed Wed Sep 5, 2012 03:39:25 PM MDT

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Step 1: Nested Regional Tomography Method

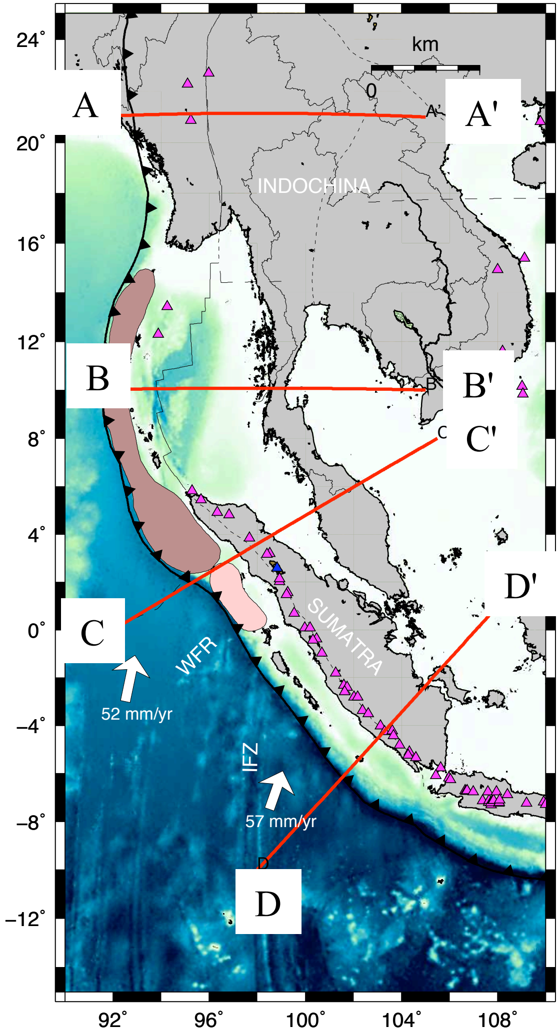


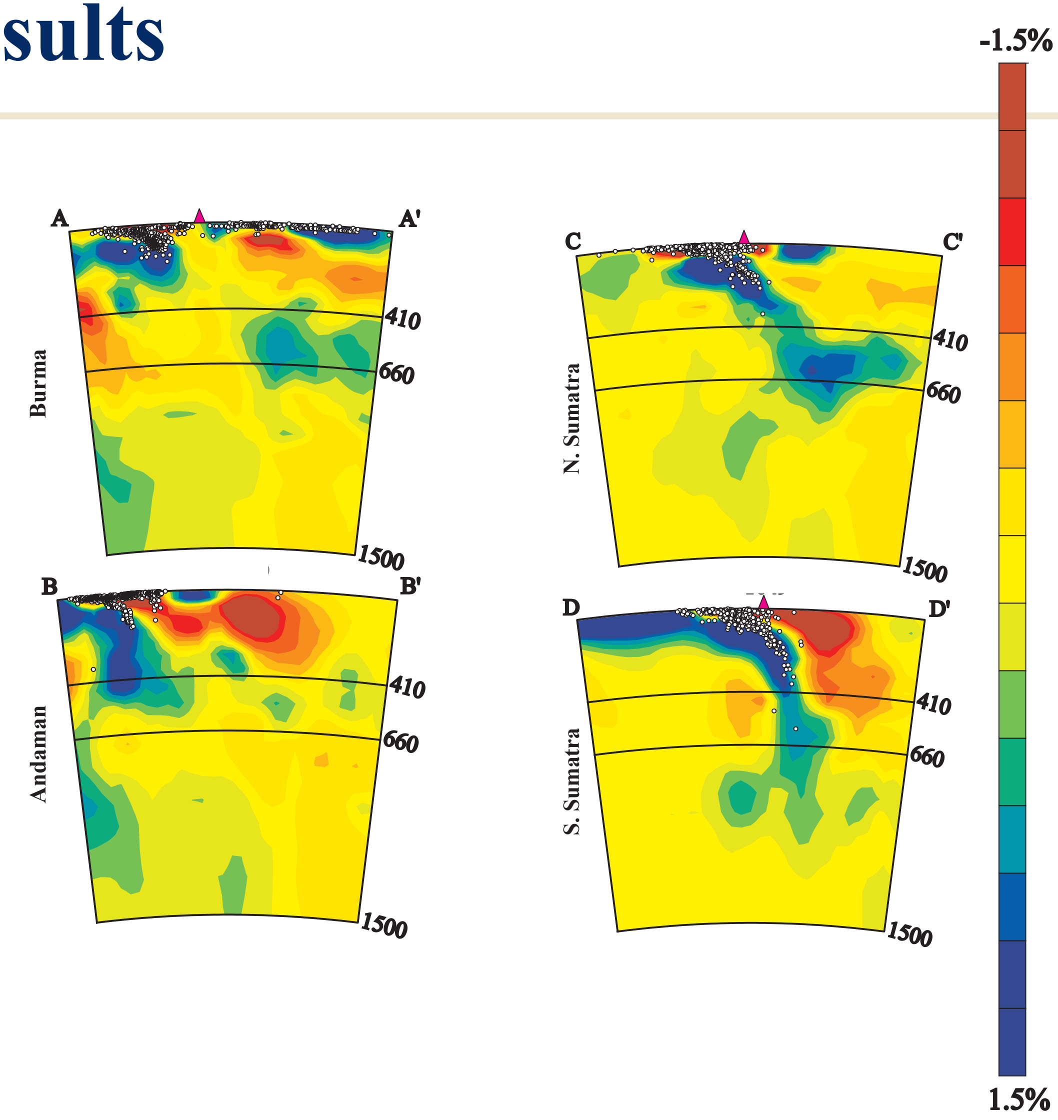
Global 5° cells
16 Layers (to 2889 km depth)

Regional 0.5° cells
19 Layers (to 1500 km depth)

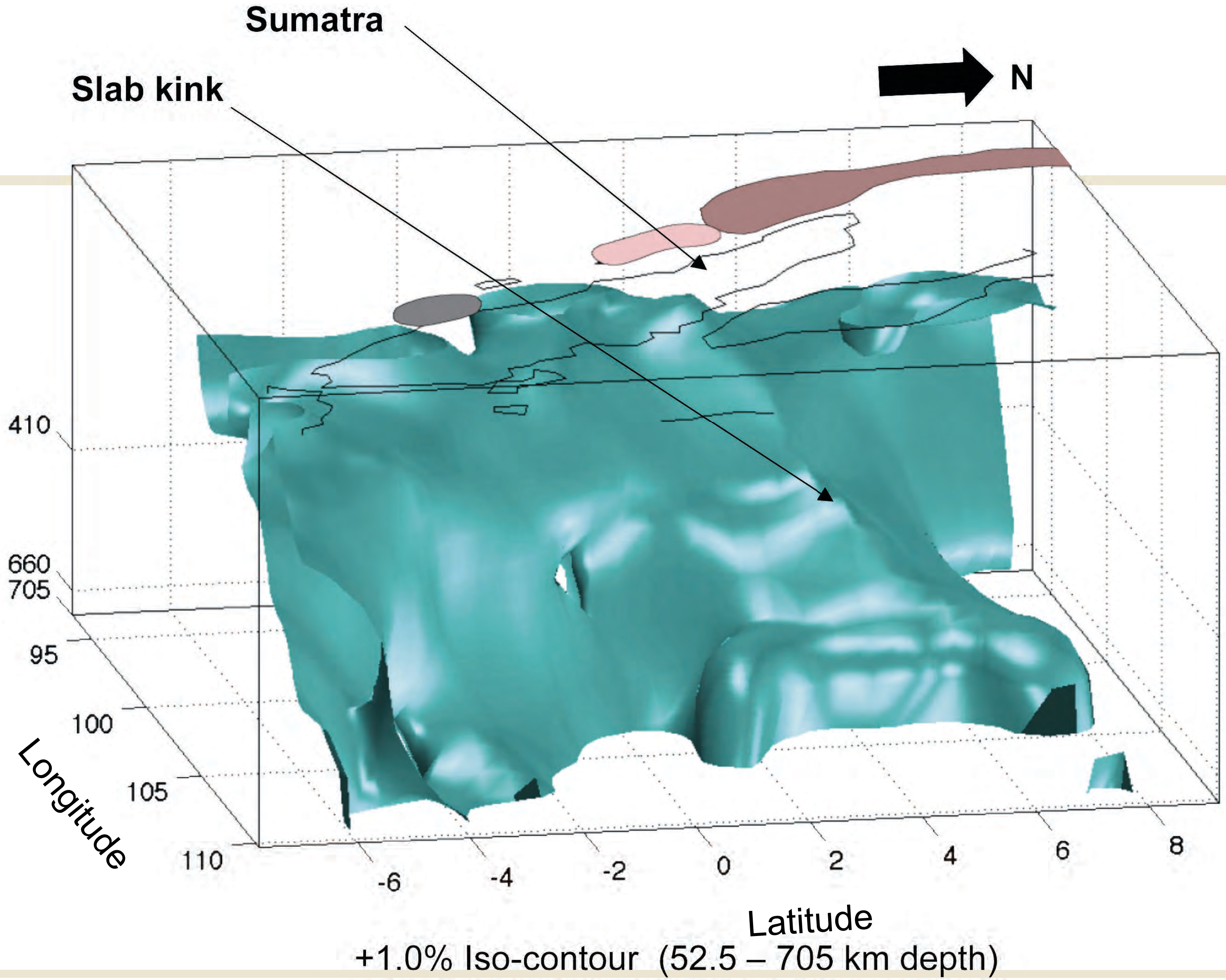
Based on Widiyantoro and van der Hilst (1996)

Single Iteration Results





From *Pesicek et al.*, 2008



+1.0% Iso-contour (52.5 – 705 km depth)

From *Pesicek et al.*, 2008

2007 M8+ Southern Sumatra Earthquakes
Coseismic Slip & Aftershocks