Working Toward a Community South America Convergent Margin Model

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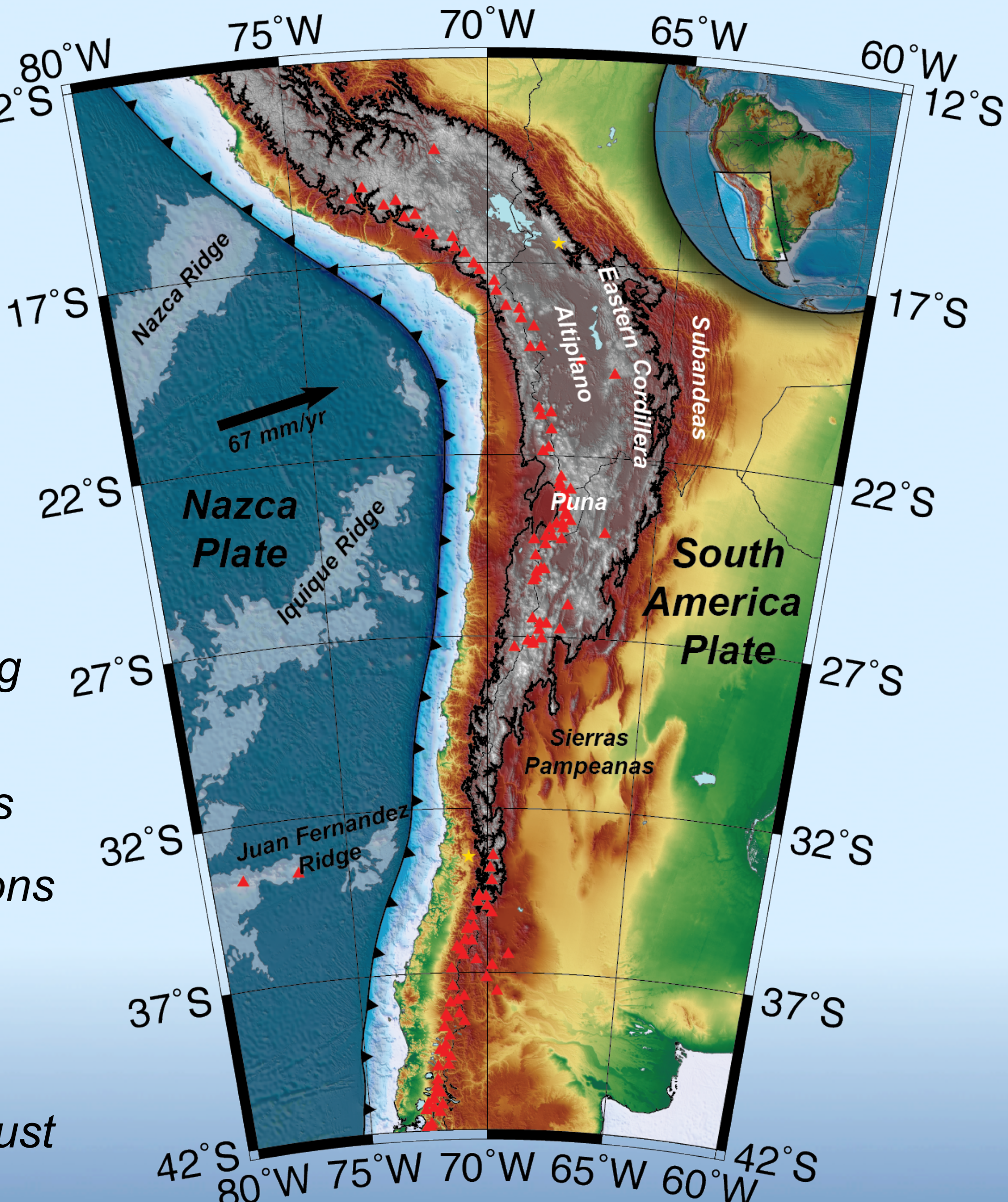
Why Study the South America Subduction Zone & Convergent Margin?

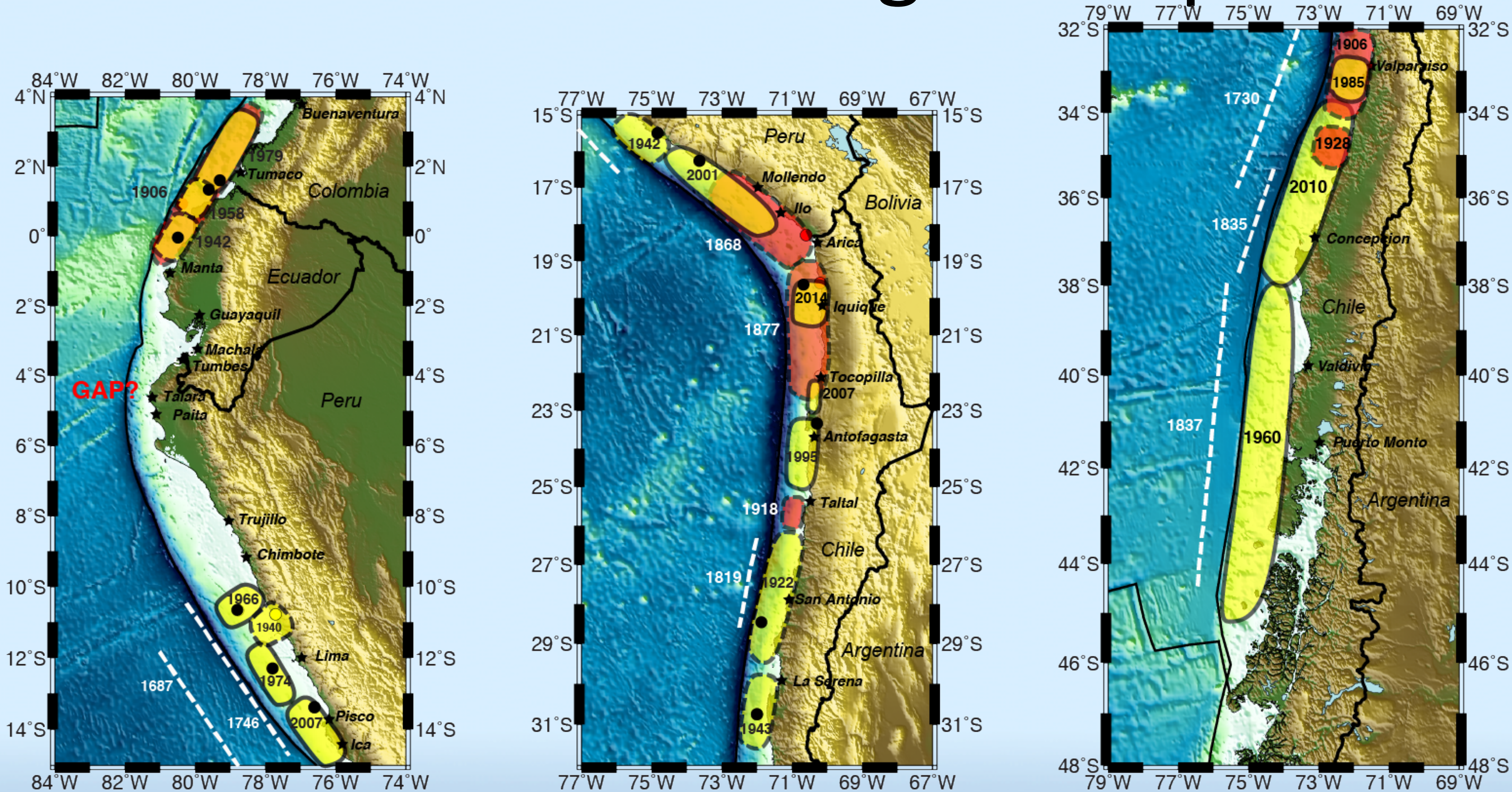
- *One of Earth's largest and long-lived ocean-continent subduction zone*
- *World's largest subduction zone earthquake, tsunamis & damaging intraplate earthquakes*
- *Large number of active volcanoes*
- *Along strike and temporal variations in slab geometry & subduction*
- *Location of one of Earth's largest continental plateaus (>3 km elevation) and major retro-arc thrust belt – Andes - tectonics*
- *Major population centers at risk*



Earthquakes & Seismic Imaging of Earth Structure

1. *Earthquake rupture, segmentation along strike, and up & down dip – maximum size earthquake, and tsunami modeling for inundation projections*
2. *Geometry of the subducting Nazca slab down to ~800 km*
3. *Improved crustal structure with an example of imaging crustal scale magma bodies associated with active arc volcanoes)*
4. *Different styles of flat slab subduction in Peru and Chile/Argentina*

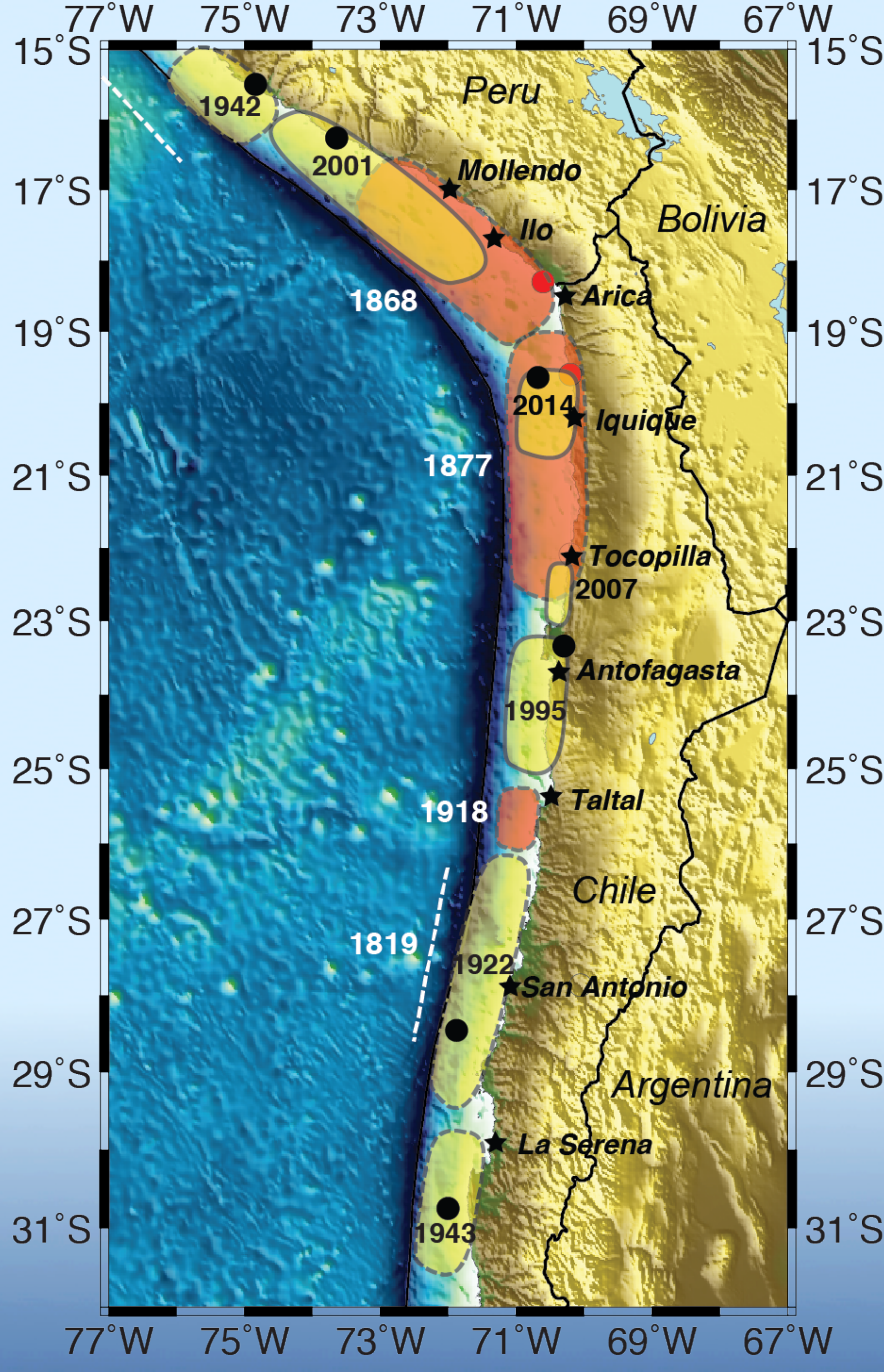
Tsunami Generating Earthquakes



- *South American subduction zone plate boundary generates M>8 earthquake on average every decade*
- *Coastal cities have been wiped out from historic tsunamis!*
- *As population & infrastructure grow along the coast the risk is increasing!*

Northern Chile

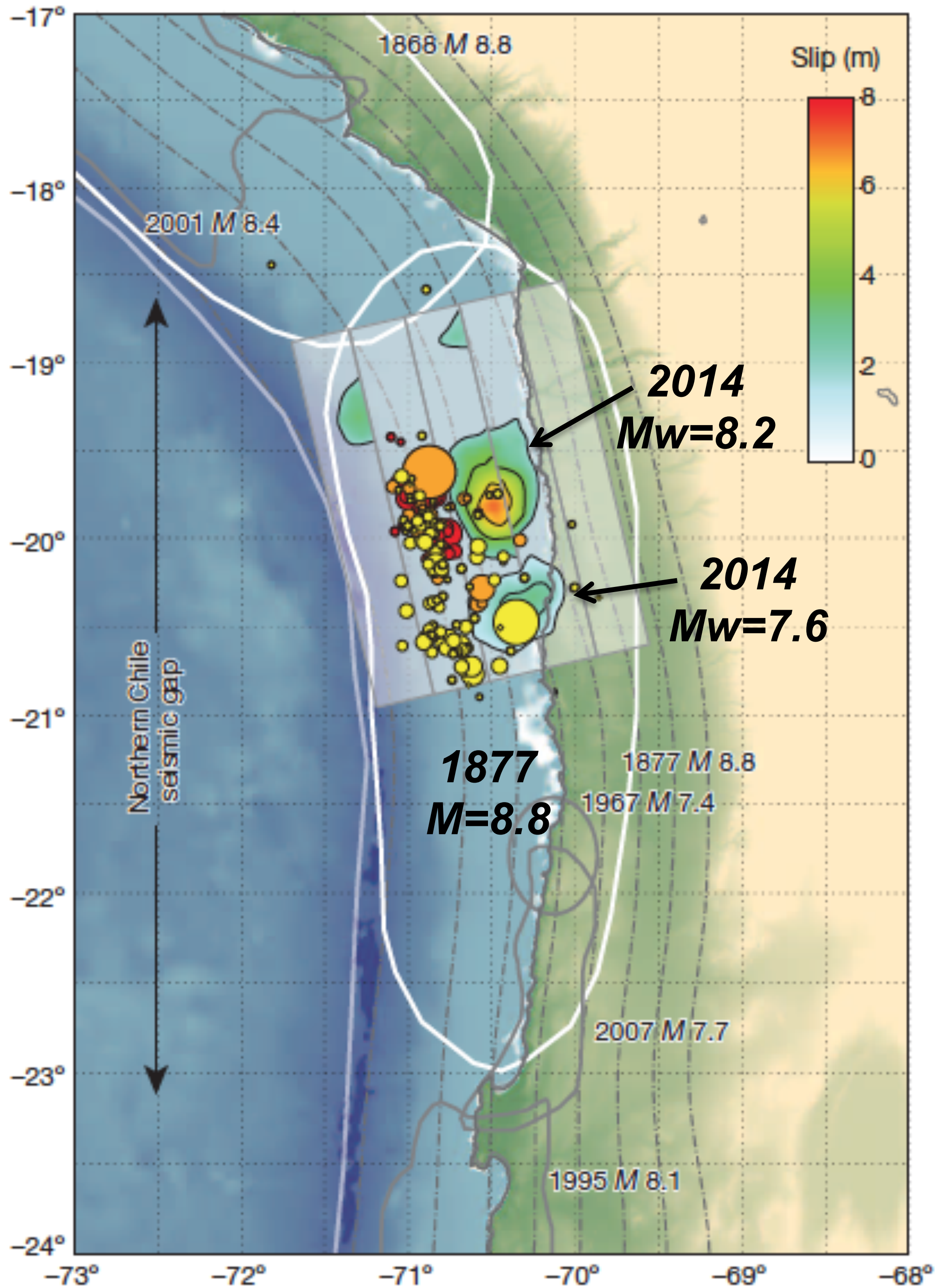
- *2014 Iquique earthquake ruptured part of the 1877 rupture zone leaving a ~200 km gap*
- *Repeat of the 1922 earthquake or a series of small earthquakes?*
- *Coastal populations at risk*



2014 Iquique Earthquake

- *More earthquakes to come?*
- *What controls the variation in rupture mode between events along the same segment?*
- *What controls the fault segmentation along strike?*
- *What if any features are long term segment boundaries or barriers?*
- *Are there foreshocks and precursory information?*

Hayes et al., 2014

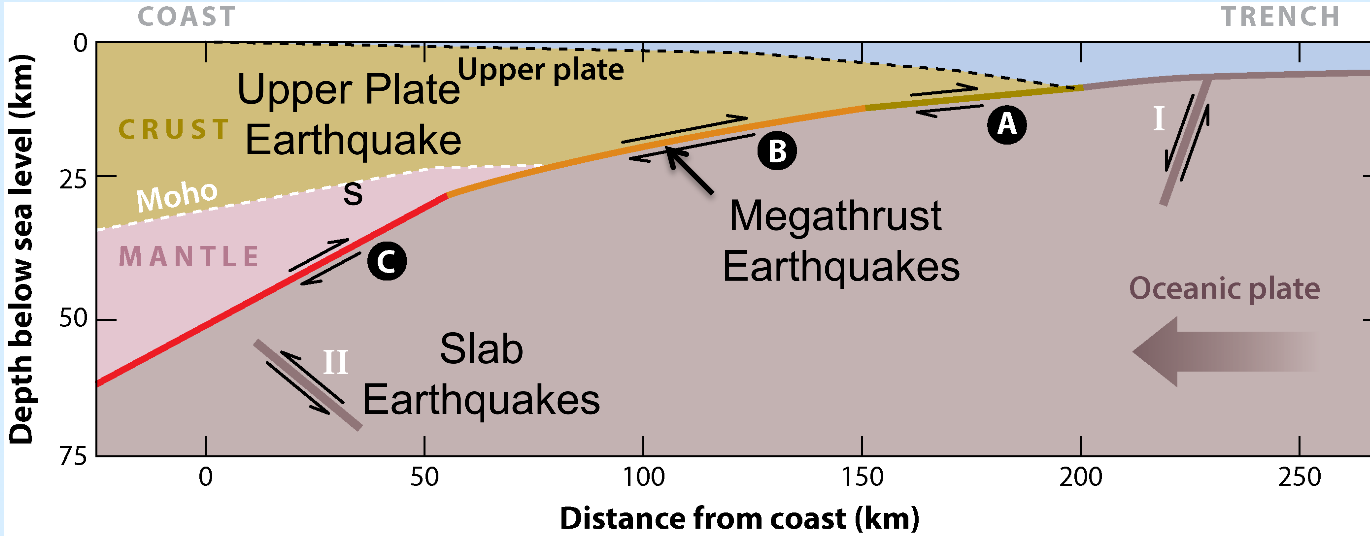


Earthquake Segmentation

A. <u>Near trench domain</u> region can produce slow earthquakes with unusually large tsunamis

B. <u>Megathrust domain</u> region of great earthquakes and co-seismic slip

C. <u>Down dip domain</u> region with moderate earthquakes and region that can produce slow slip events or tremors



Kanamori H. 2014. Annu. Rev. Earth Planet. Sci. 42:7–26

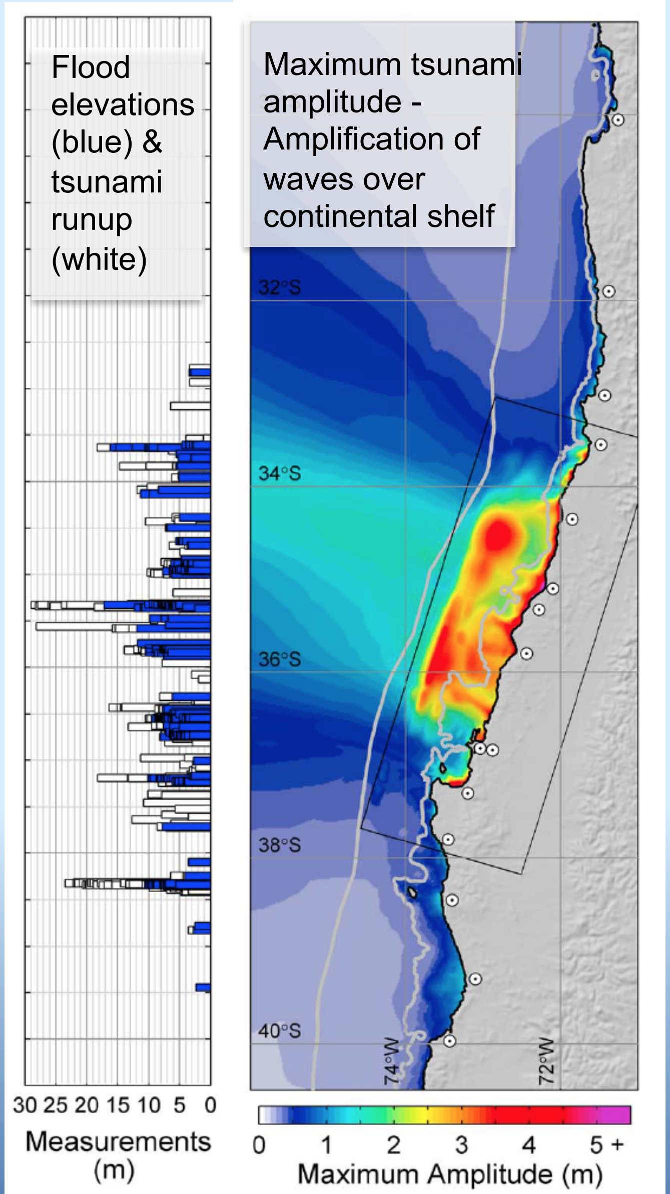
Modified from Lay et al., , 2012

- *What controls the fault segmentation up- and down-dip?*
- *Are there foreshocks and precursory information?*
- *What is the long term plate coupling?*
- *Are there slow slip events up-dip or down-dip and how are they related to the great megathrust events?*

Tsunamis

- *Continental shelf and coastal bathymetry causes large variations in local & regional Tsunami height*
- *We need Tsunami propagation and inundation projections accounting for:*
  - *Earthquake size, fault geometry, slip pattern, co-seismic uplift & subsidence*
  - *Continental shelf, bathymetry & coastline*
  - *Sea level rise (dynamic)*
  - *Tides*
- *Produce maps identifying regions of projected large tsunamis along with maps of coastal regions with critical infrastructure*

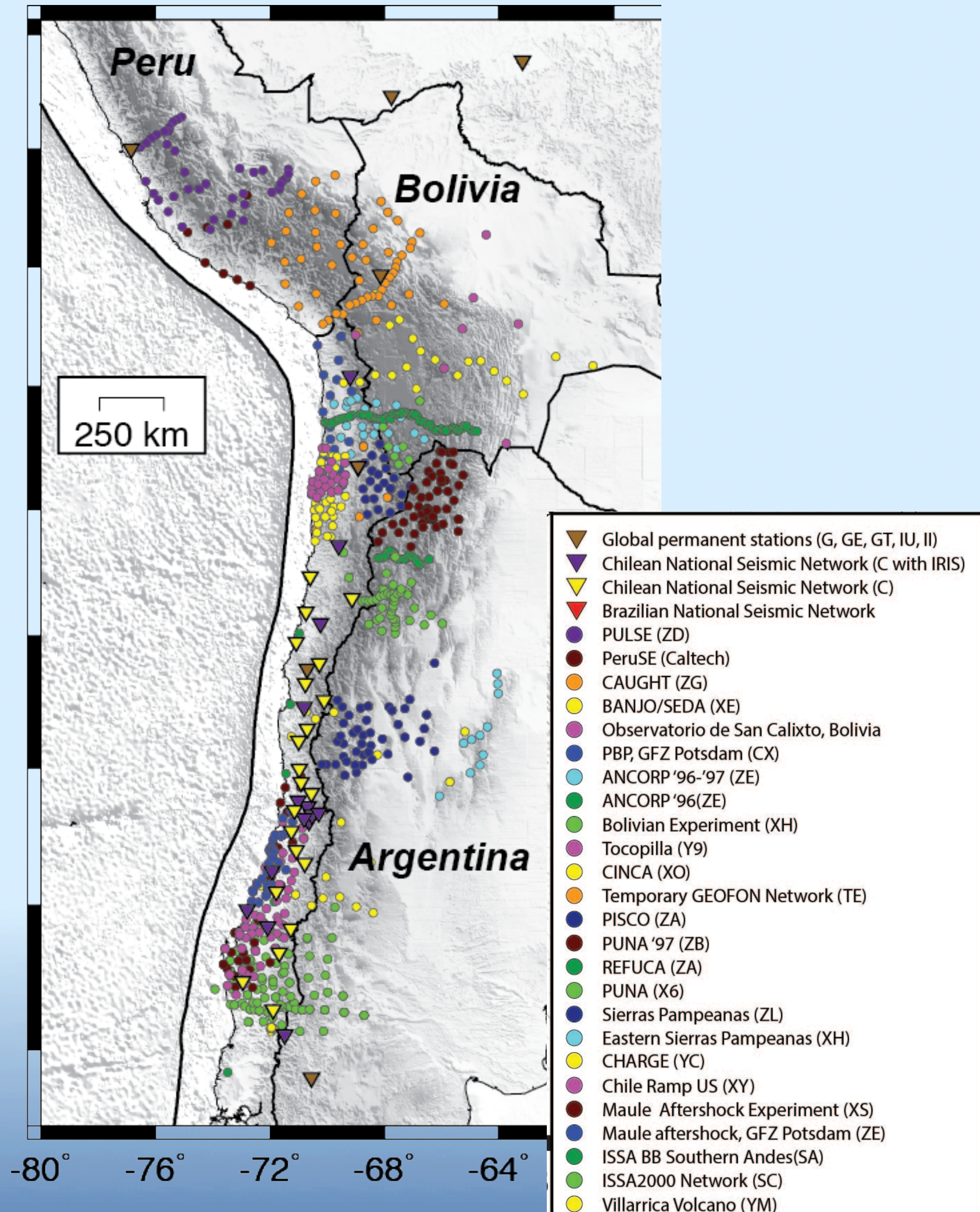
2010 Maule Earthquake Tsunami



Yamazaki and Cheung (2011)

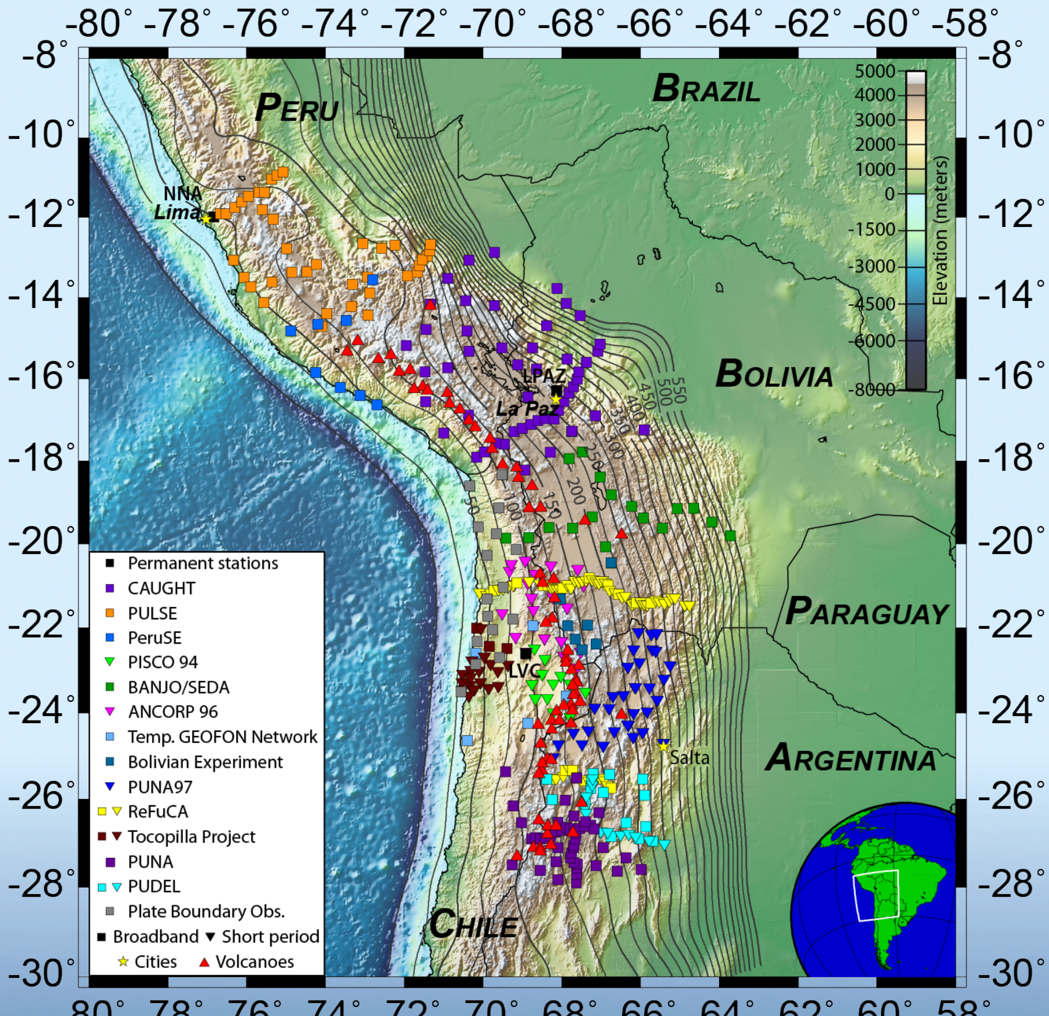
Seismic data 1994-2014

- *Over the past 20 years there have been many broadband and short-period seismic deployments in the Andes*
- *We used open data from ~600 seismic stations –thanks to efforts of in-country and international groups that collected and archived the digital data!*
- *We are combining data from all of these deployments to image the subduction zone and convergent margin in a systematic way*
- *Thanks to the IRIS PASSCAL program and IRIS DMC and funding from NSF*



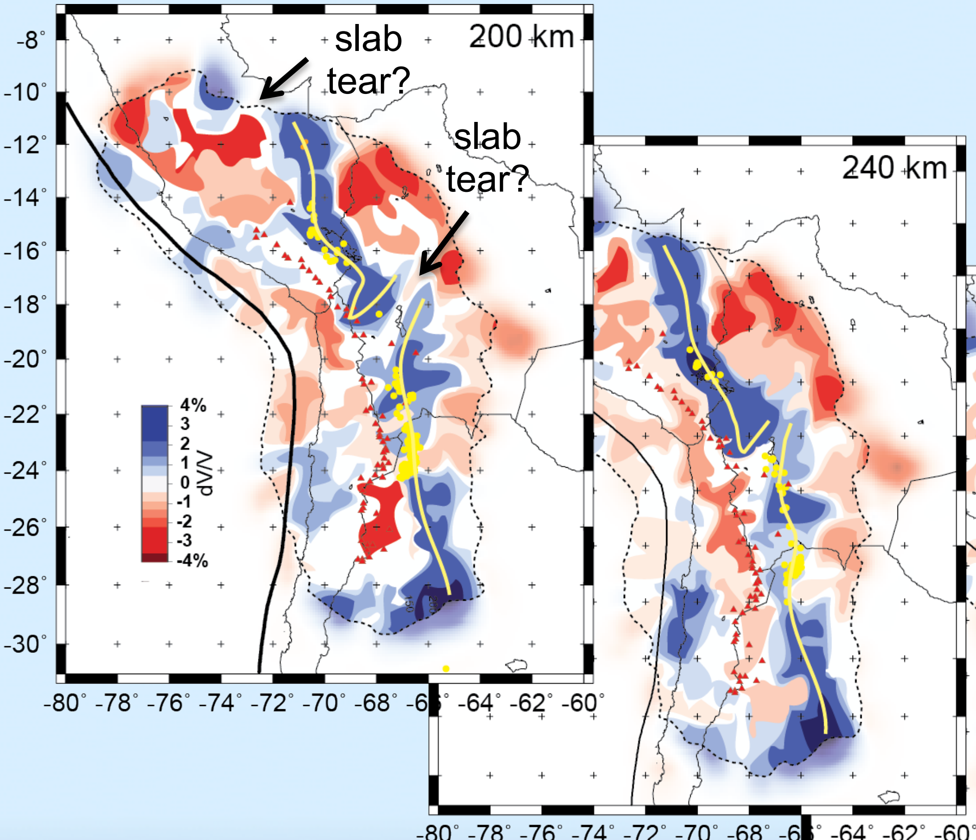
Teleseismic Tomography to Image the Subduction Zone

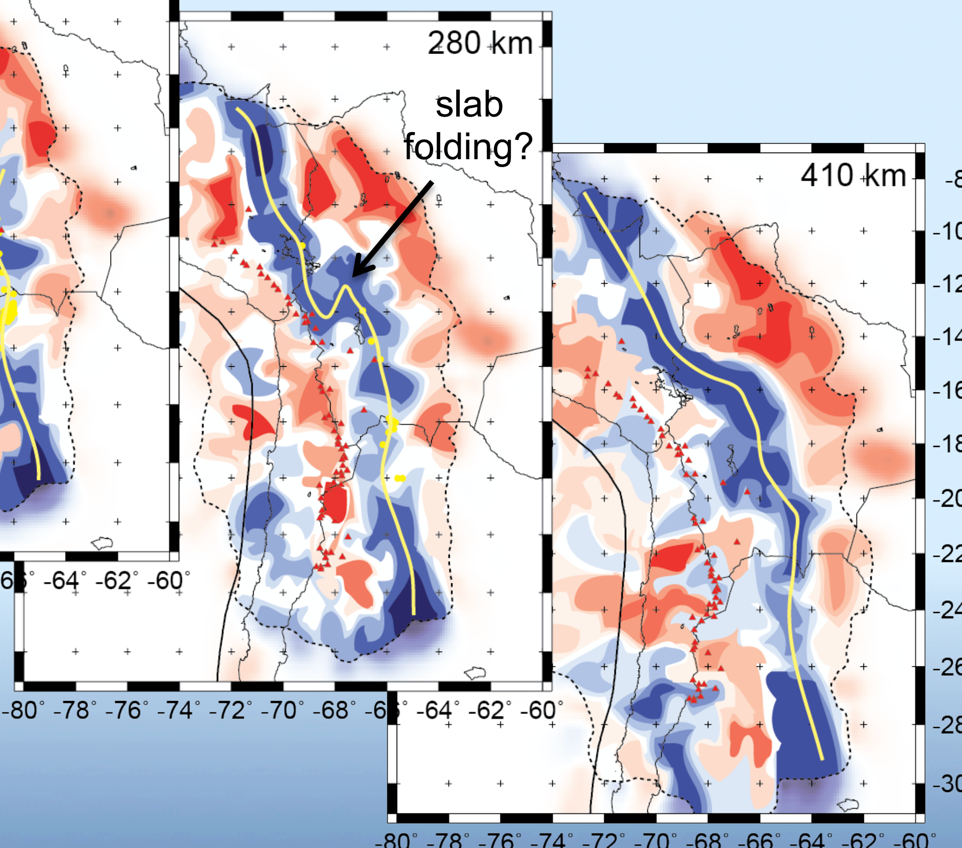
- *Finite frequency teleseismic tomography using the method of Schmandt & Humphreys, 2010*
- *Data from 546 earthquakes recorded on 384 stations resulting in 27,435 P phase picks*
- *Crustal thickness correction included*



Teleseismic P-wave Tomography

- Slab imaged starting at ~150-200 km
- Some variations from slab1.0 (Hayes et al., 2011)

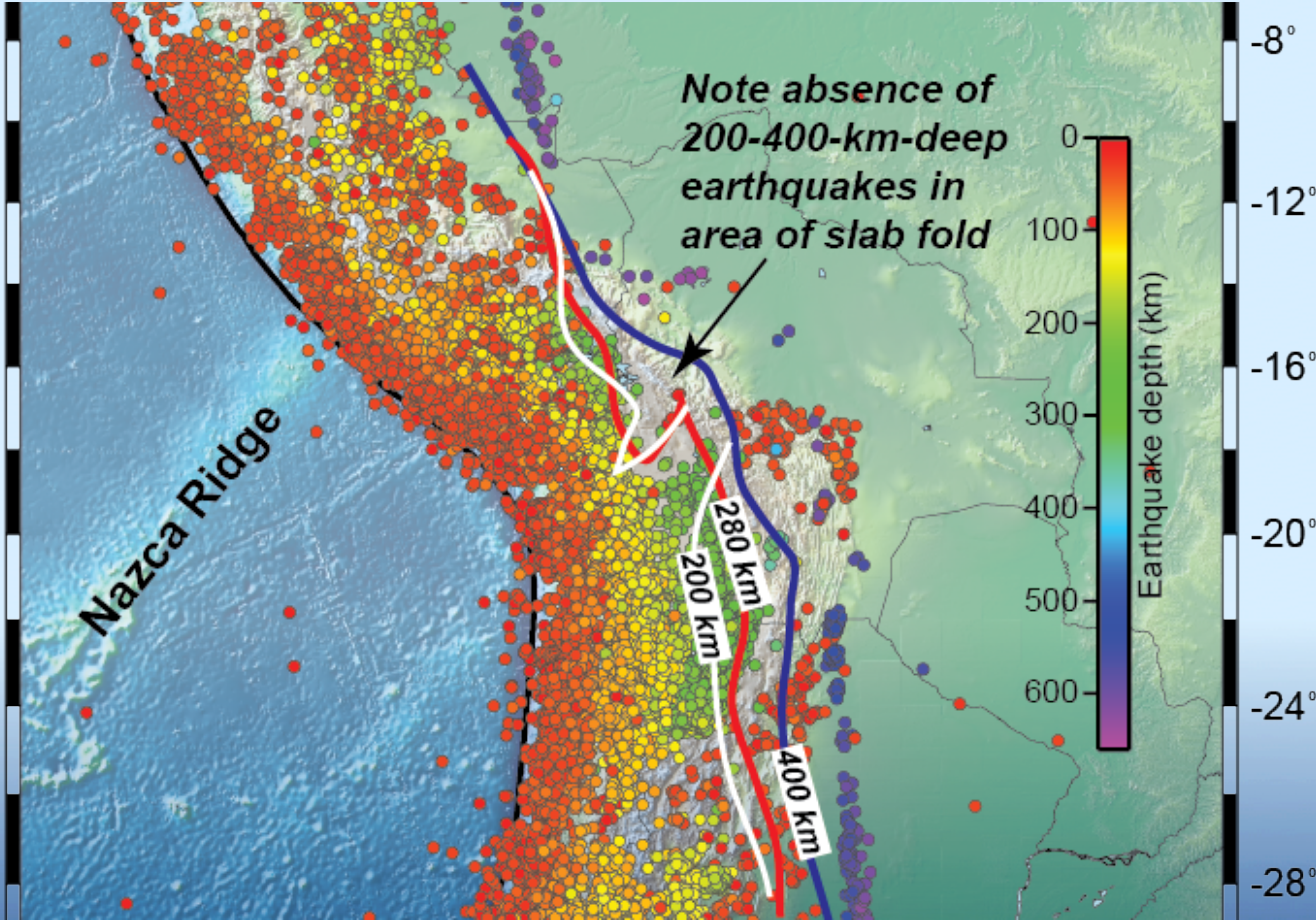




- Slab appears to be folded near ~280 km depth with a possible tear above that depth

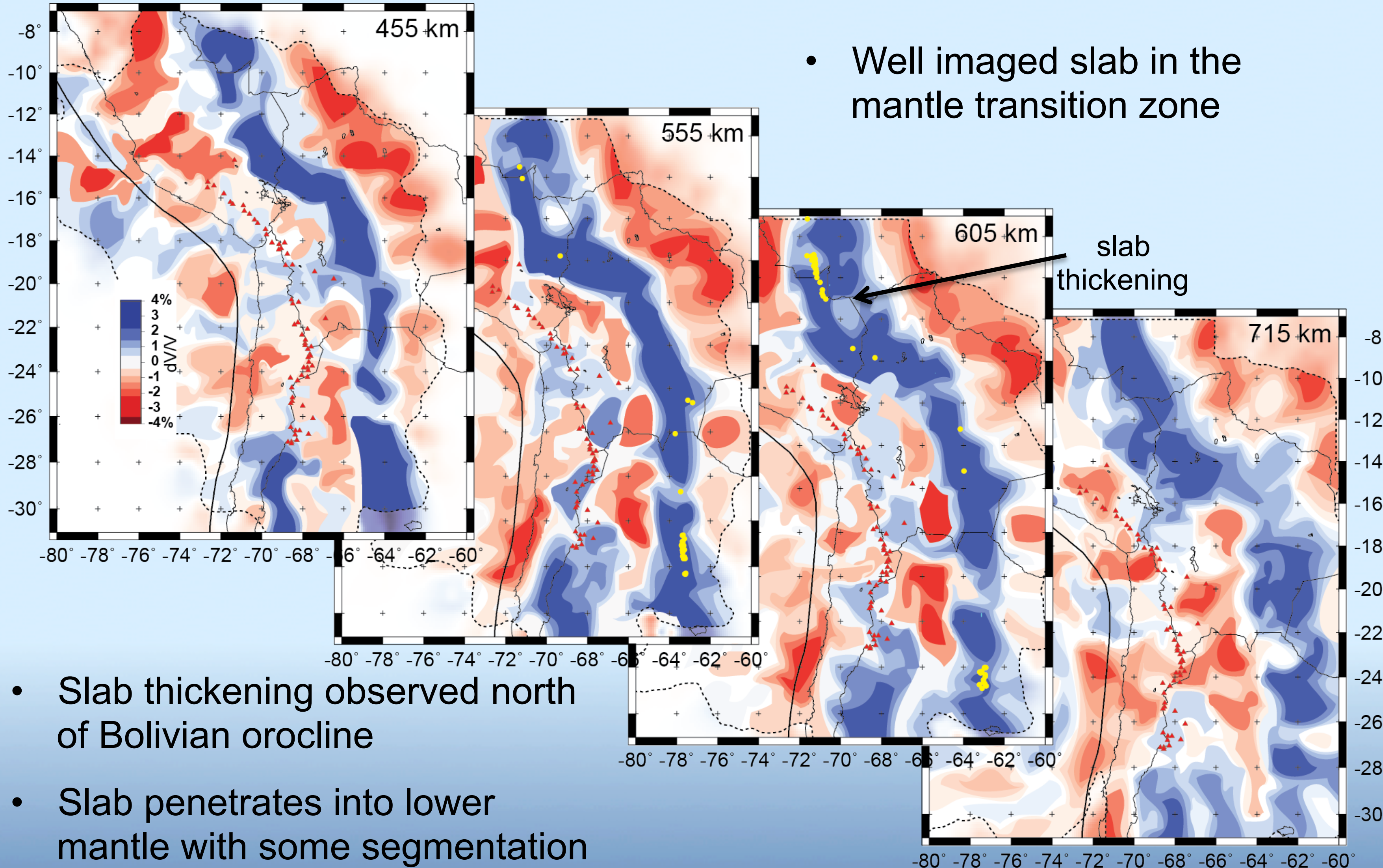
Scire et al., 2015

Earthquakes and Slab Folding



Teleseismic P-wave Tomography

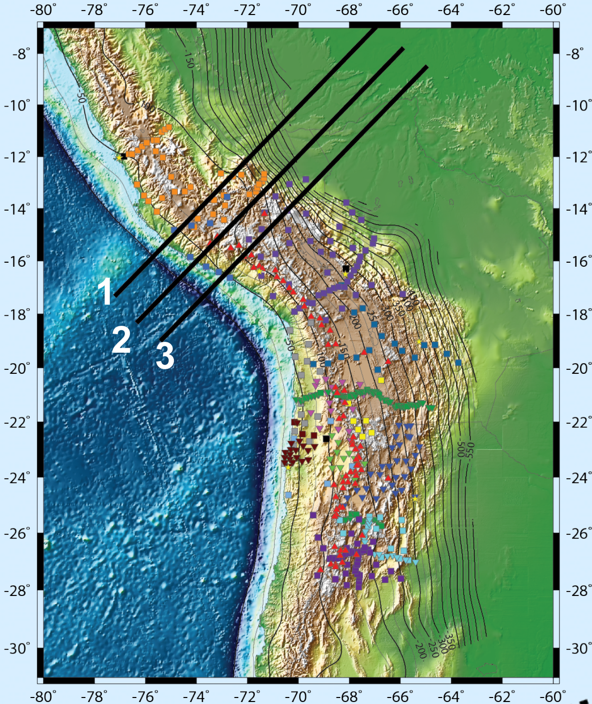
- Well imaged slab in the mantle transition zone



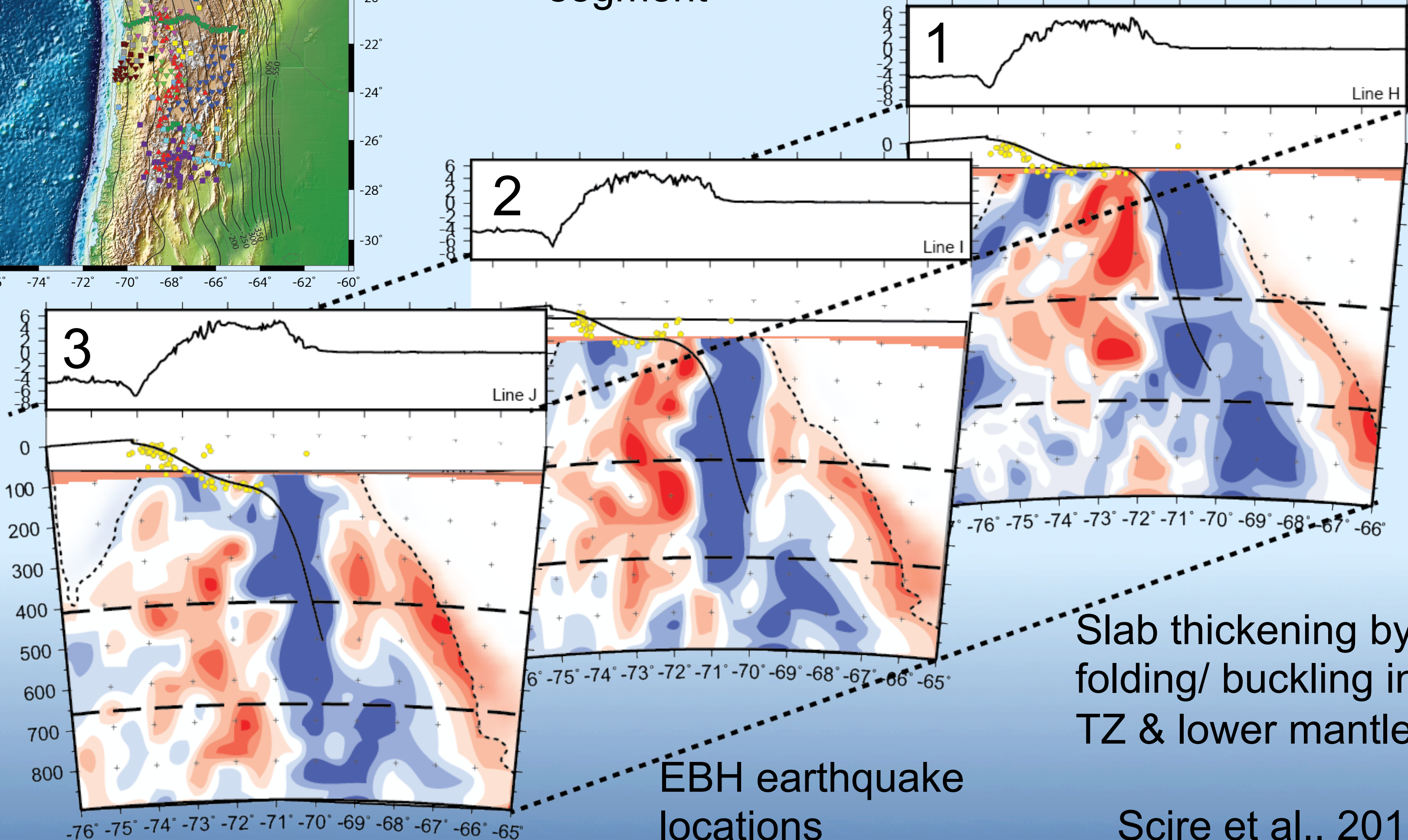
- Slab thickening observed north of Bolivian orocline
- Slab penetrates into lower mantle with some segmentation south of the orocline

Scire et al., 2015

P-wave Tomography



Vertical slab inboard of Peru “flat slab” segment



Slab thickening by folding/ buckling in TZ & lower mantle

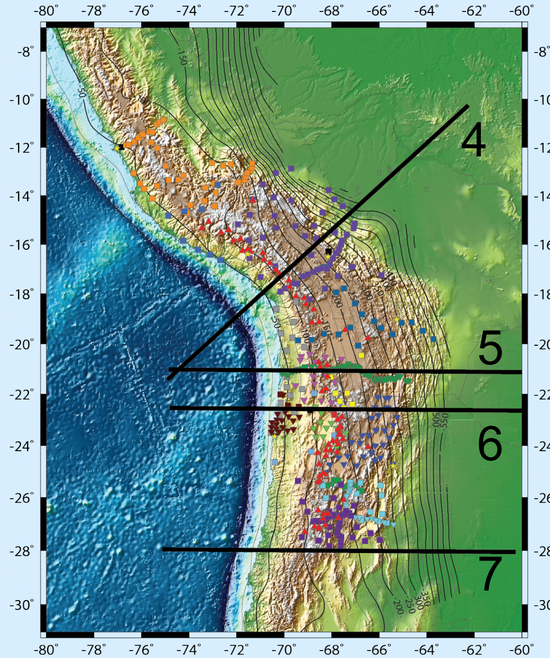
EBH earthquake locations

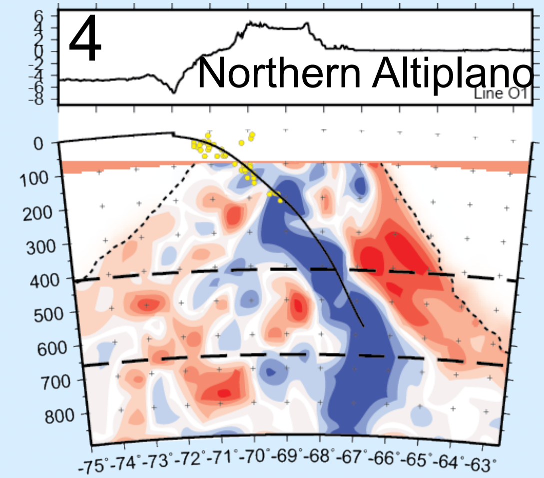
Scire et al., 2015

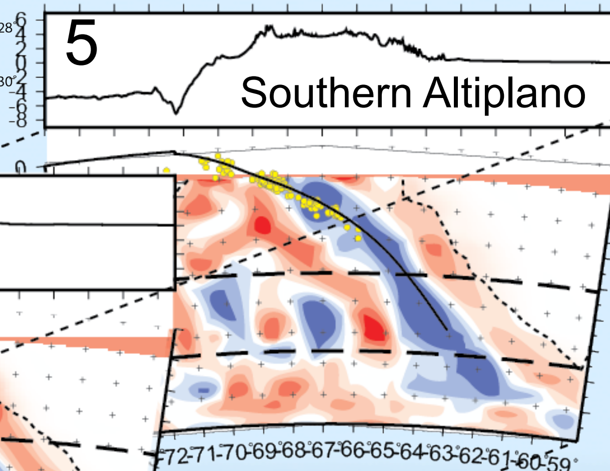
P-wave Tomography

North of the Bolivian orocline the slab penetrates steeply into the lower mantle

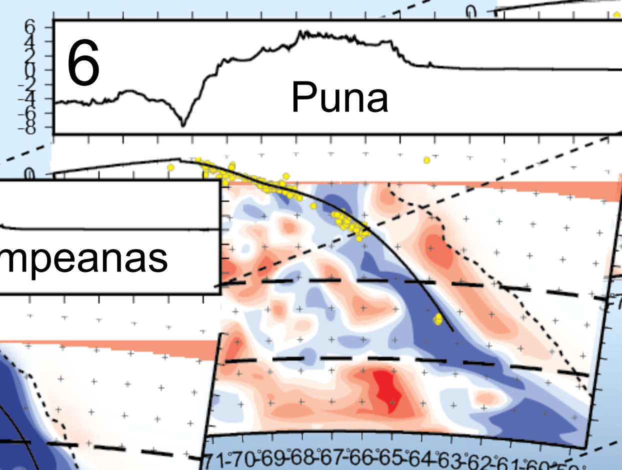
South of the Bolivian orocline the slab dip shallows, flattening?

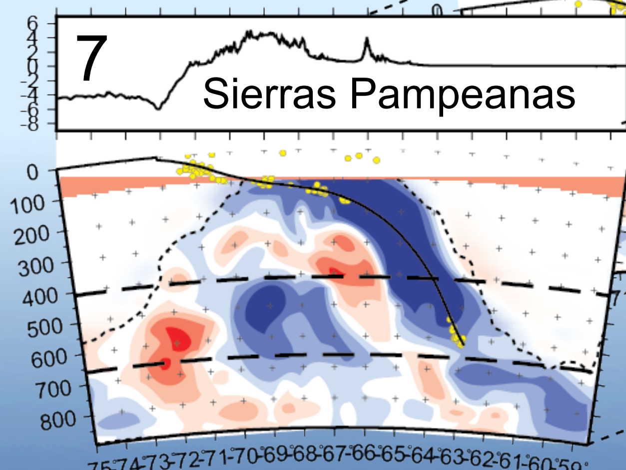






EBH earthquake locations

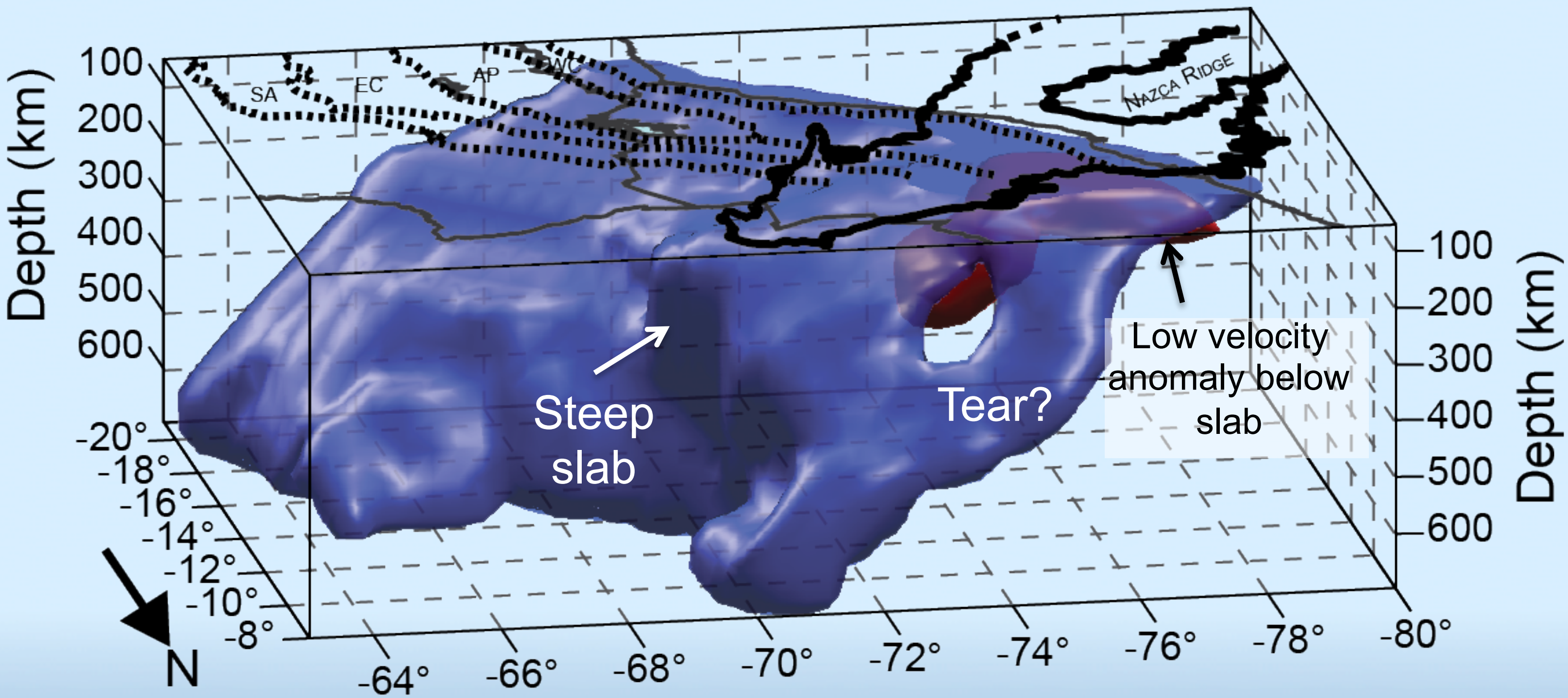




Slab still penetrates the 670 km discontinuity but with shallow dip

Scire et al., 2015

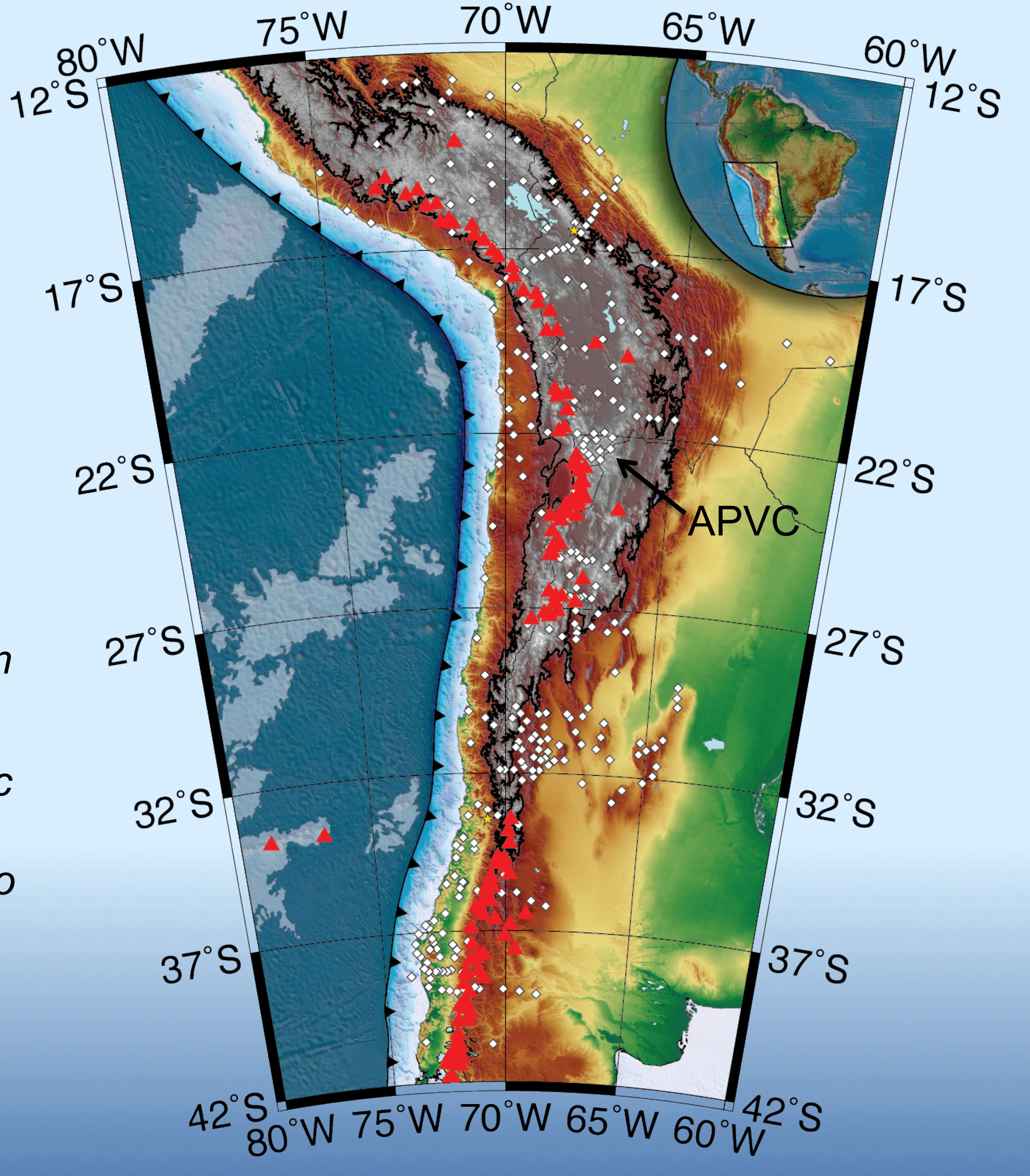
Nazca Slab Geometry from P-wave Tomography – North Central Andes



Scire et al., 2015

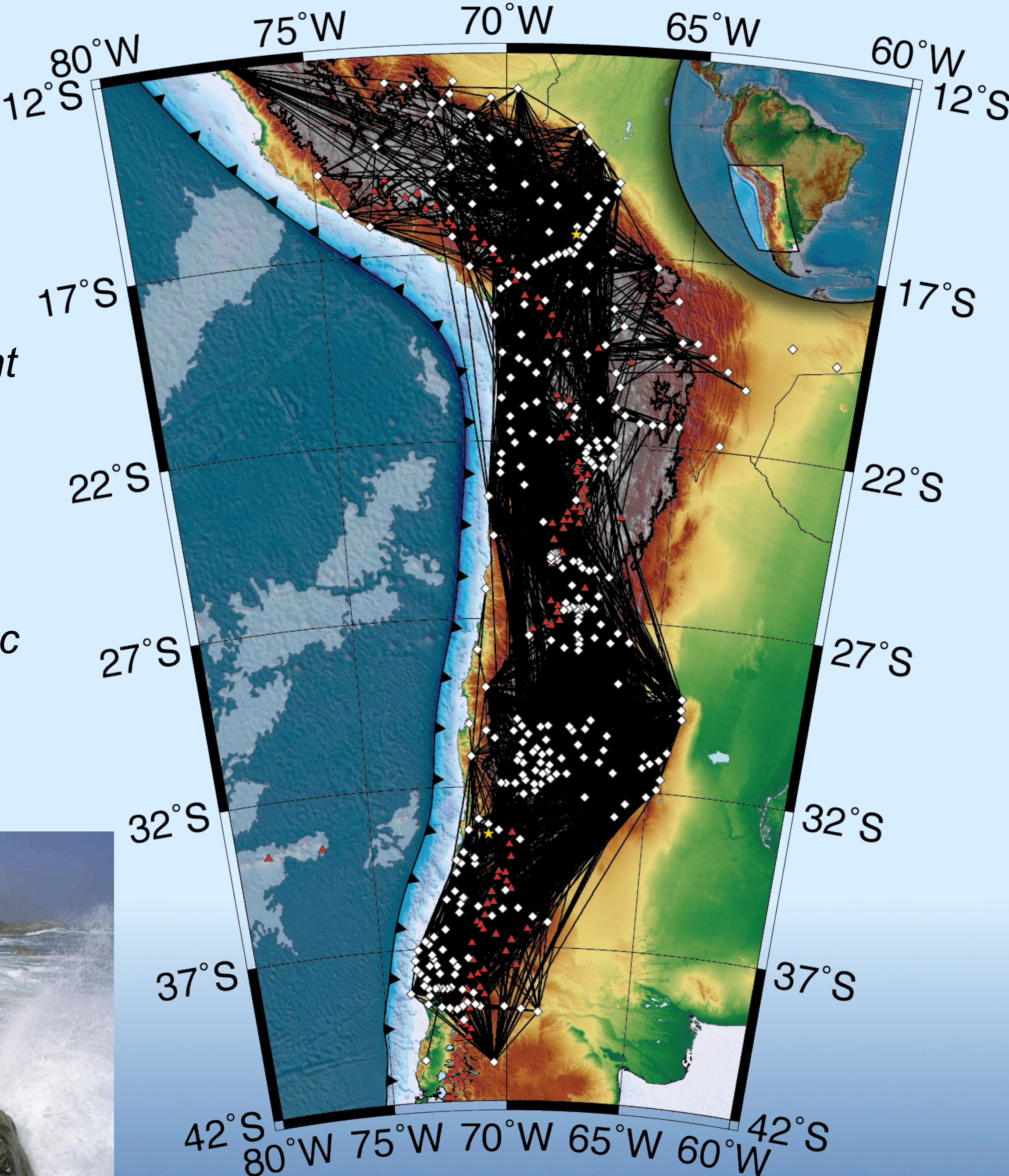
Crustal Structure & Magmatic Processes

- *Active volcanic arc and locally abundant backarc volcanism*
- *Is there a magma body or MUSH zone associated with this active volcanism?*
- *Can we improve the seismic image of the magma body associated with the Altiplano Puna Volcanic Complex?*



Ambient Noise Tomography

- *Cross correlate ambient noise on vertical component broad-band data from 330 stations to obtain Rayleigh waves*
- *Determine phase velocity maps between 8 and 40 sec*
- *Invert for shear velocity model*

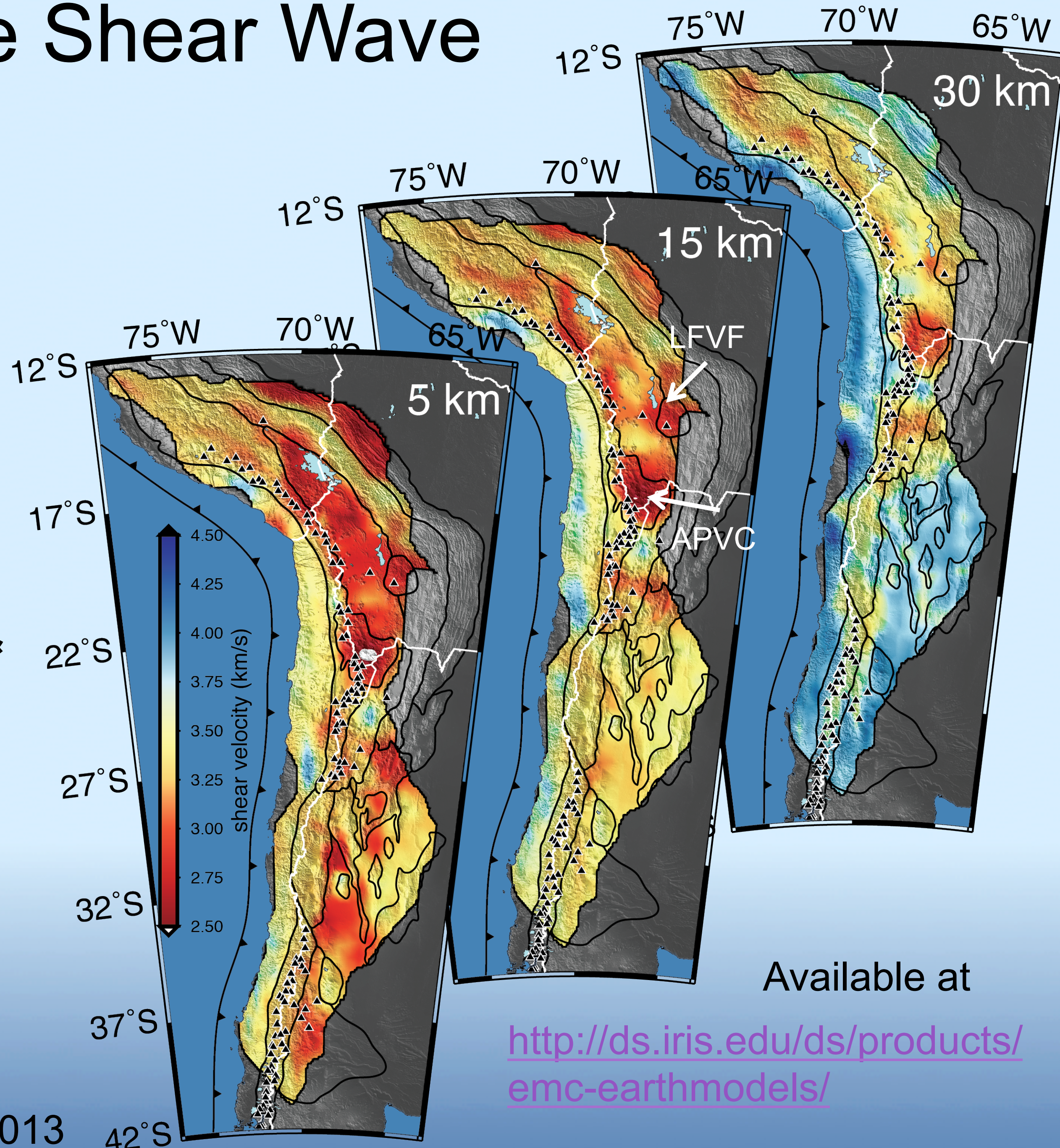


Ward et al., GJI, 2013

Sources for ANT

Crustal Scale Shear Wave Model

- *Shallow crustal velocity reflects locations of basins and basement, e.g., Altiplano and E. Cordillera*
- *15-km crustal layer reveals low-velocities below major volcanic fields, e.g., Los Frailes & Altiplano Puna Volcanic Complex*
- *30-km crust shows low-velocity under CAP and high-velocity under SP*
- *Slowest crust underlies the 10Ma – 1Ma APVC silicic volcanic field*



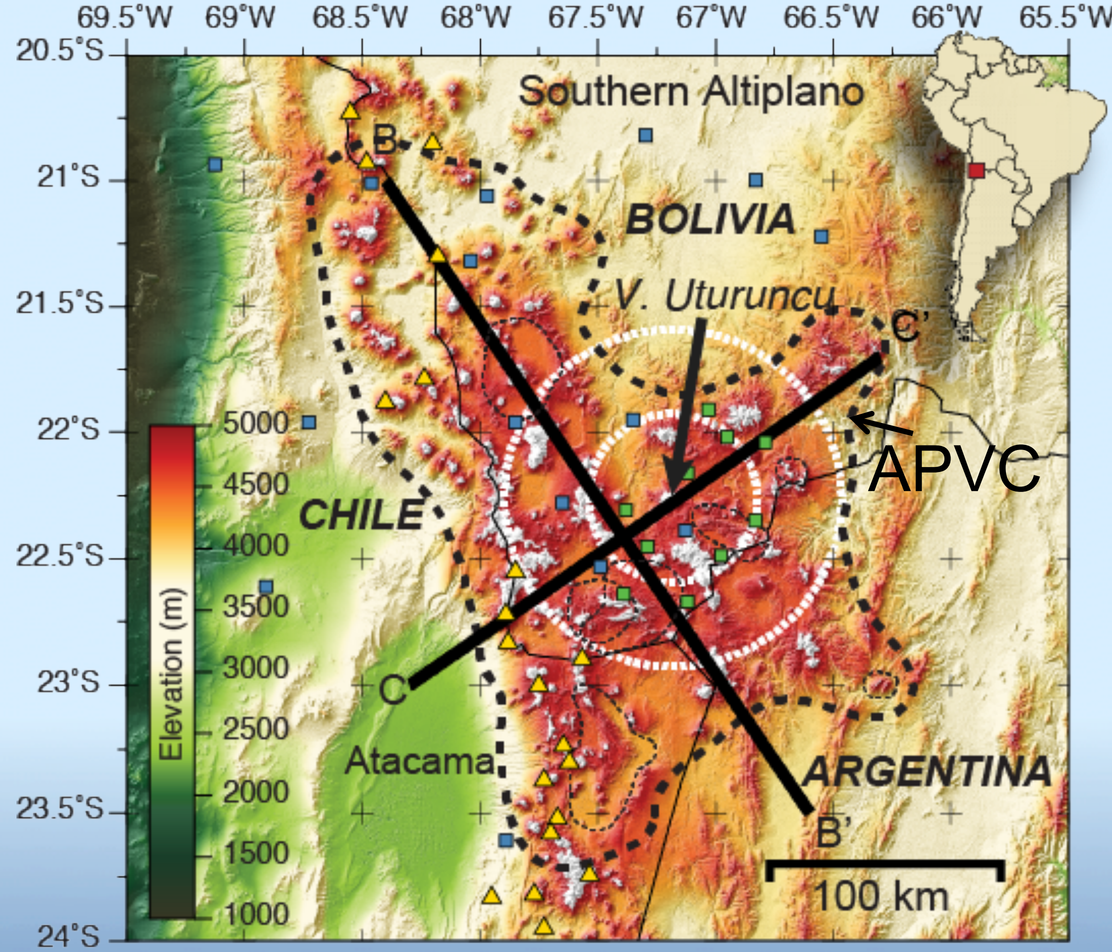
Ward et al., GJI, 2013

Available at

http://ds.iris.edu/ds/products/emc-earthmodels/

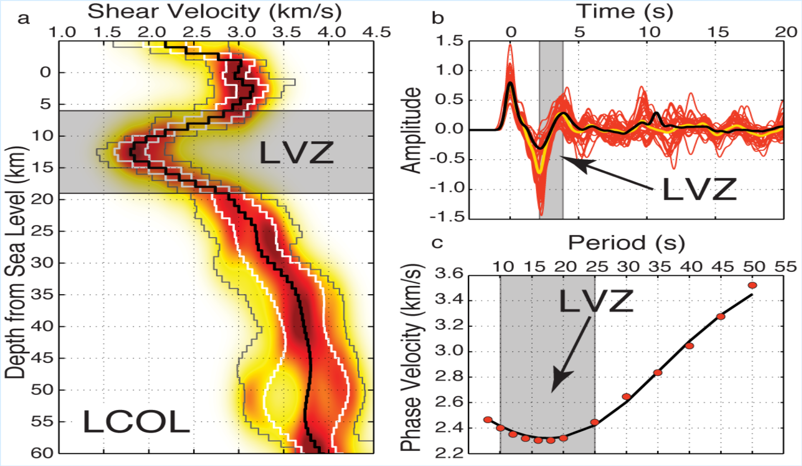
Altiplano Puna Volcanic Ignimbrite Flare up

- *The APVC is a 11-1 Ma silicic volcanic field in the southern Altiplano & northern Puna that covers ~70,000 km²*
- *Site of crustal inflation centered near the volcano Uturuncu modeled as magma source in mid-crust (Pritchard and Simons, 2004; Fialko and Pearse, 2012)*

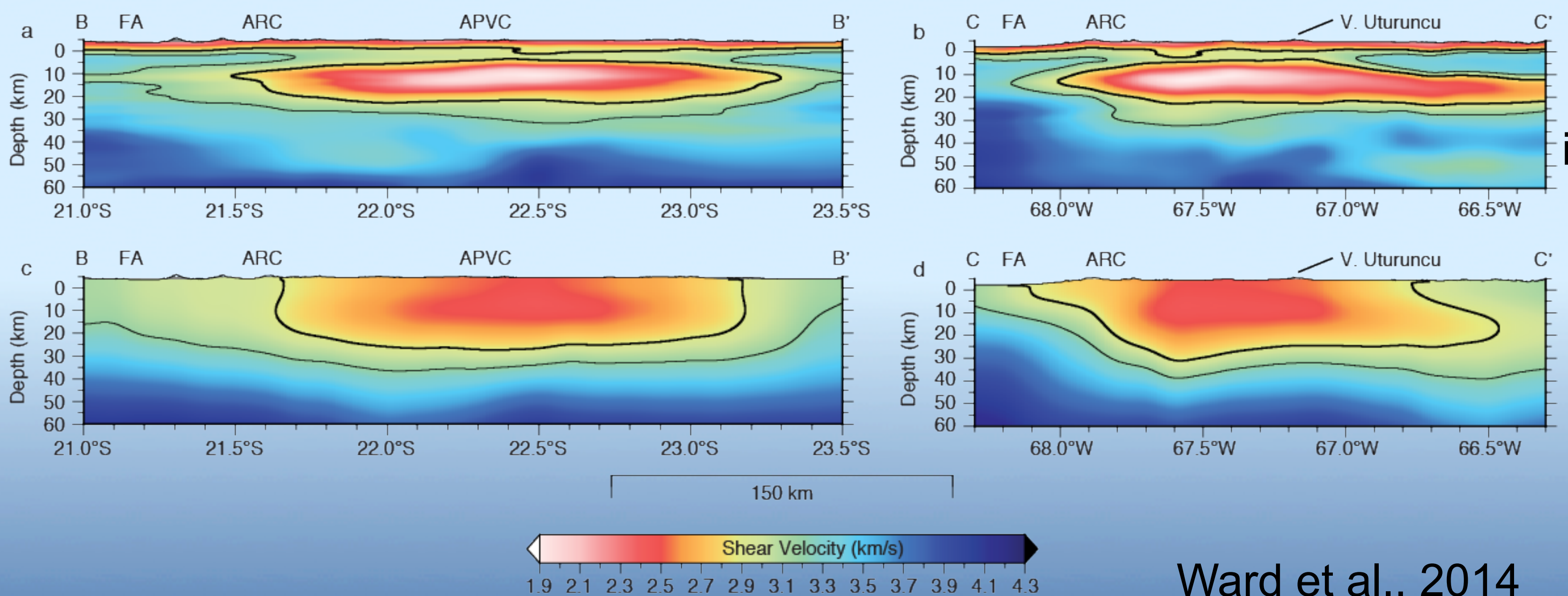


Ward et al., 2014

Joint Receiver Function – Surface Wave Dispersion Inversion



- *Joint inversion using RF and ambient noise data produces an improved shear wave velocity model for the crust*



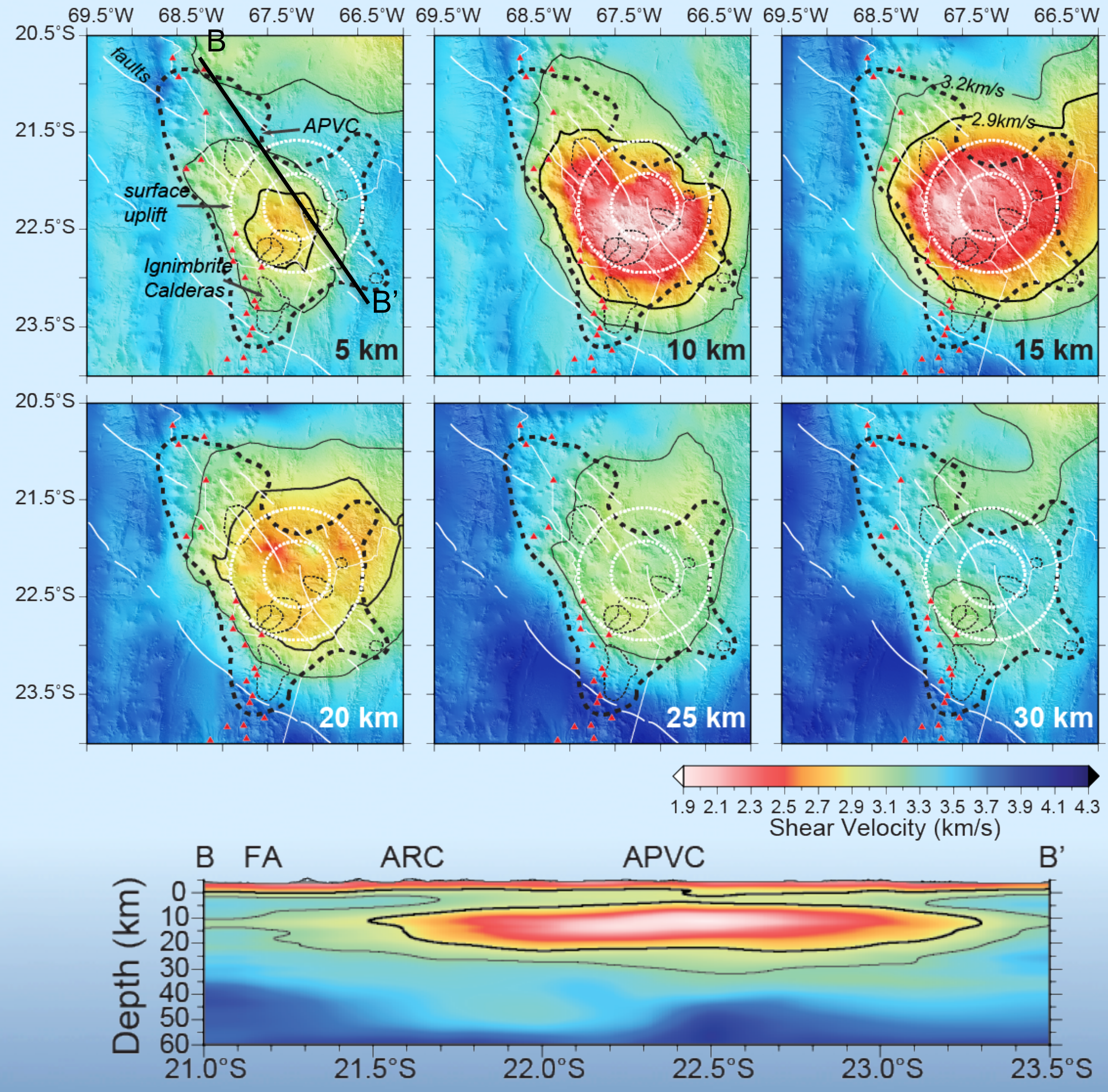
Joint inversion

ANT

Ward et al., 2014

Altiplano Puna Volcanic Complex

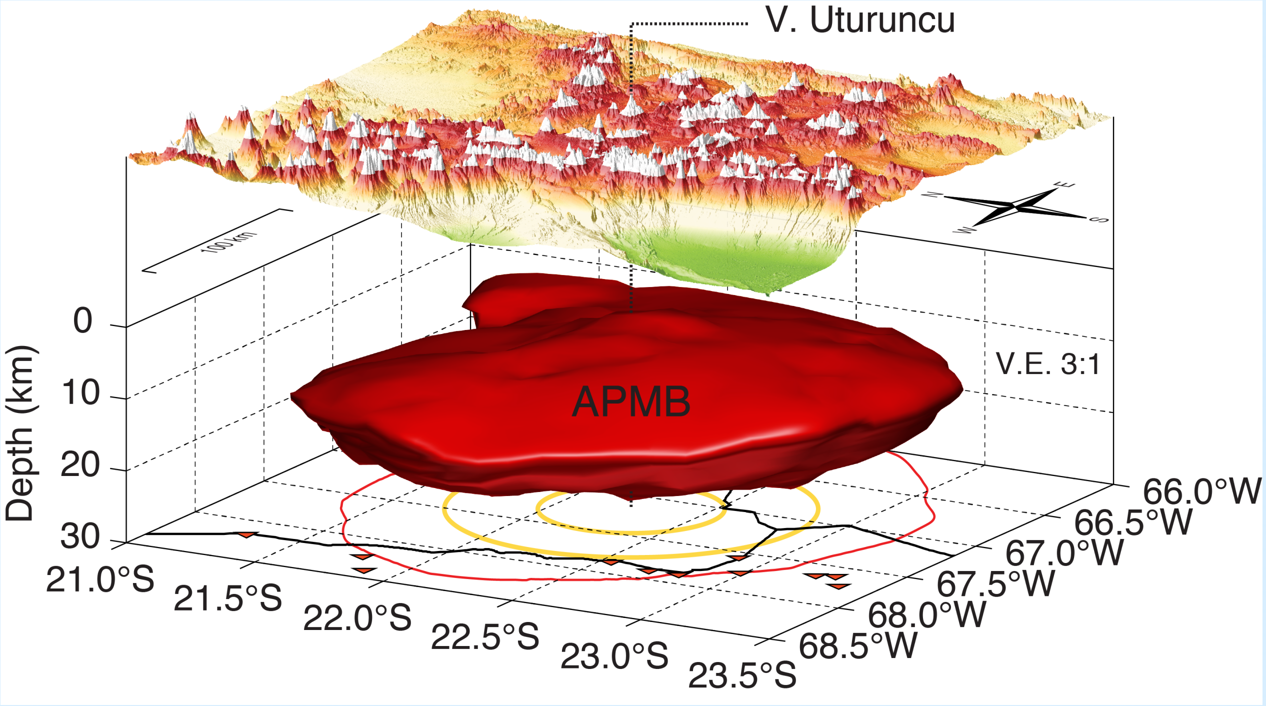
- *~200 km diameter and 11 km thick low velocity zone that we interpret as Atiplano Puna Magma Body (APMB)*
- *APMB is the still-forming plutonic complex (mush zone) associated with the APVC*
- *APMB correlates closely with large calderas, ignimbrites, and observed surface uplift centered at volcano Uturuncu*
- *The low velocity anomaly based on the 2.9 km/s contour has a volume of ~500,000 km^3*



Ward et al., 2014

3D view of the Altiplano-Puna Magma Body

- *Large volume low-velocity zone we interpret as a magmatic body (APMB)*
- *Represents a large volume magma-mush body with large component of partial melt (>20%)*
- *APMB yields a total fluid melt volume of ~75,000 km^3*
- *Suggests an extrusive to intrusive ratio of 1:25-30*

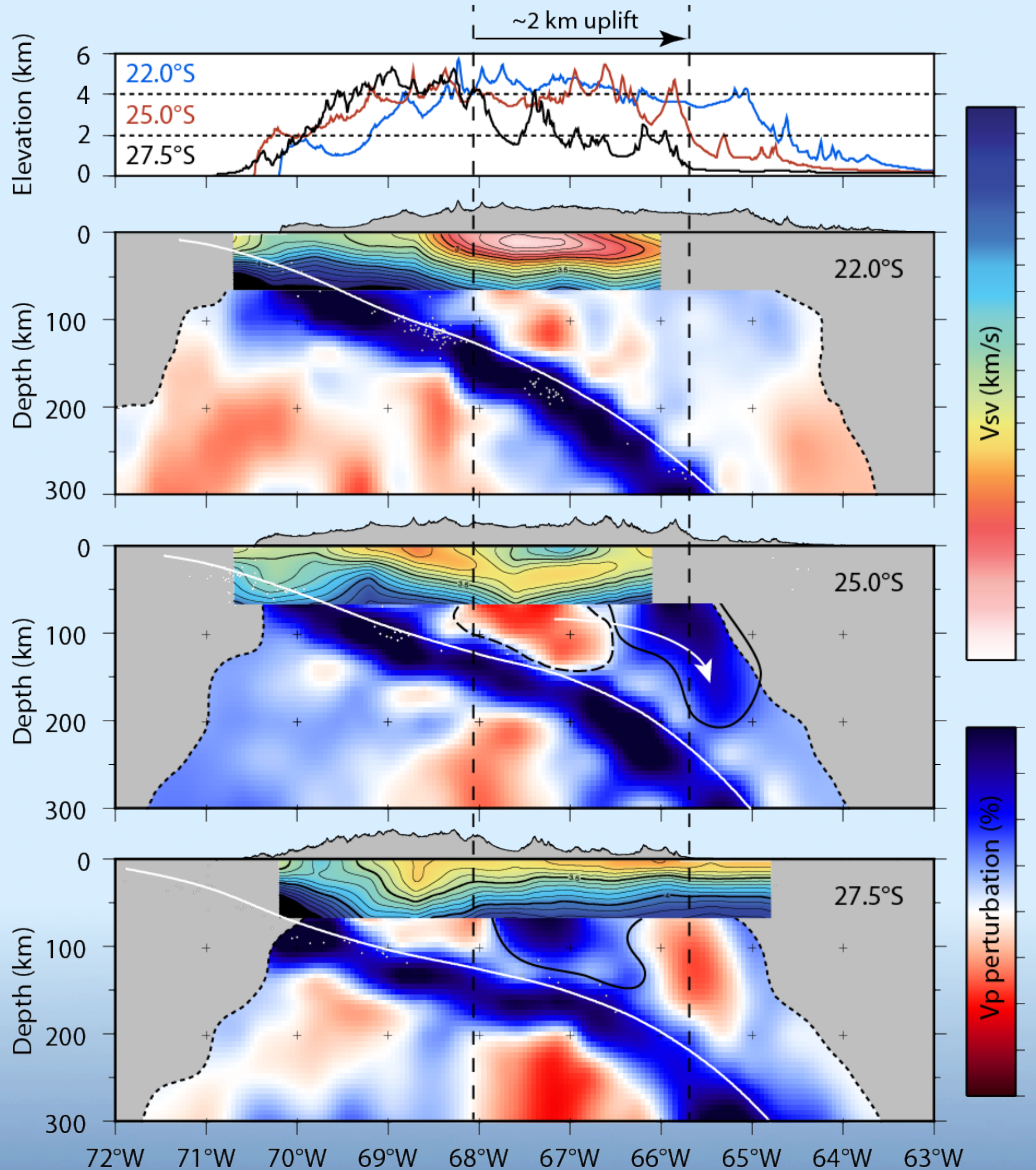


World's largest crustal magma body imaged in central Andes?

Ward et al., 2014

ANT and P-wave tomography

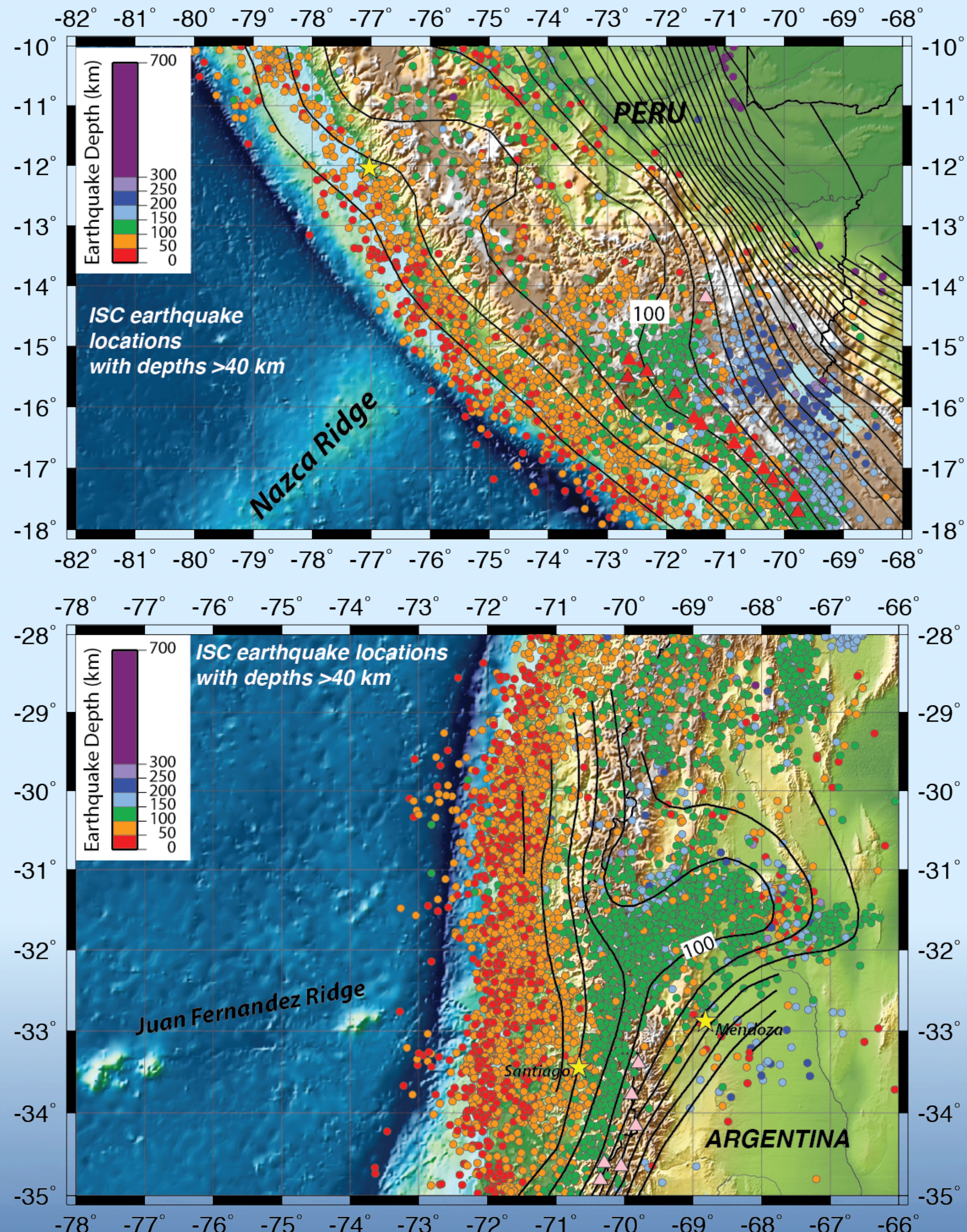
- *Combined images may show progression of lithospheric removal along strike*
- *22°S - most lithosphere is gone and large crustal low velocity body formed below the APVC*
- *25°S - lithosphere is being removed and replaced with lower velocity material*
- *27.5°S - lithosphere is still attached beneath the northern Sierras Pampeanas*
- *Changes in elevation along strike correlate with changes in lithospheric structure*



Beck et al., 2015

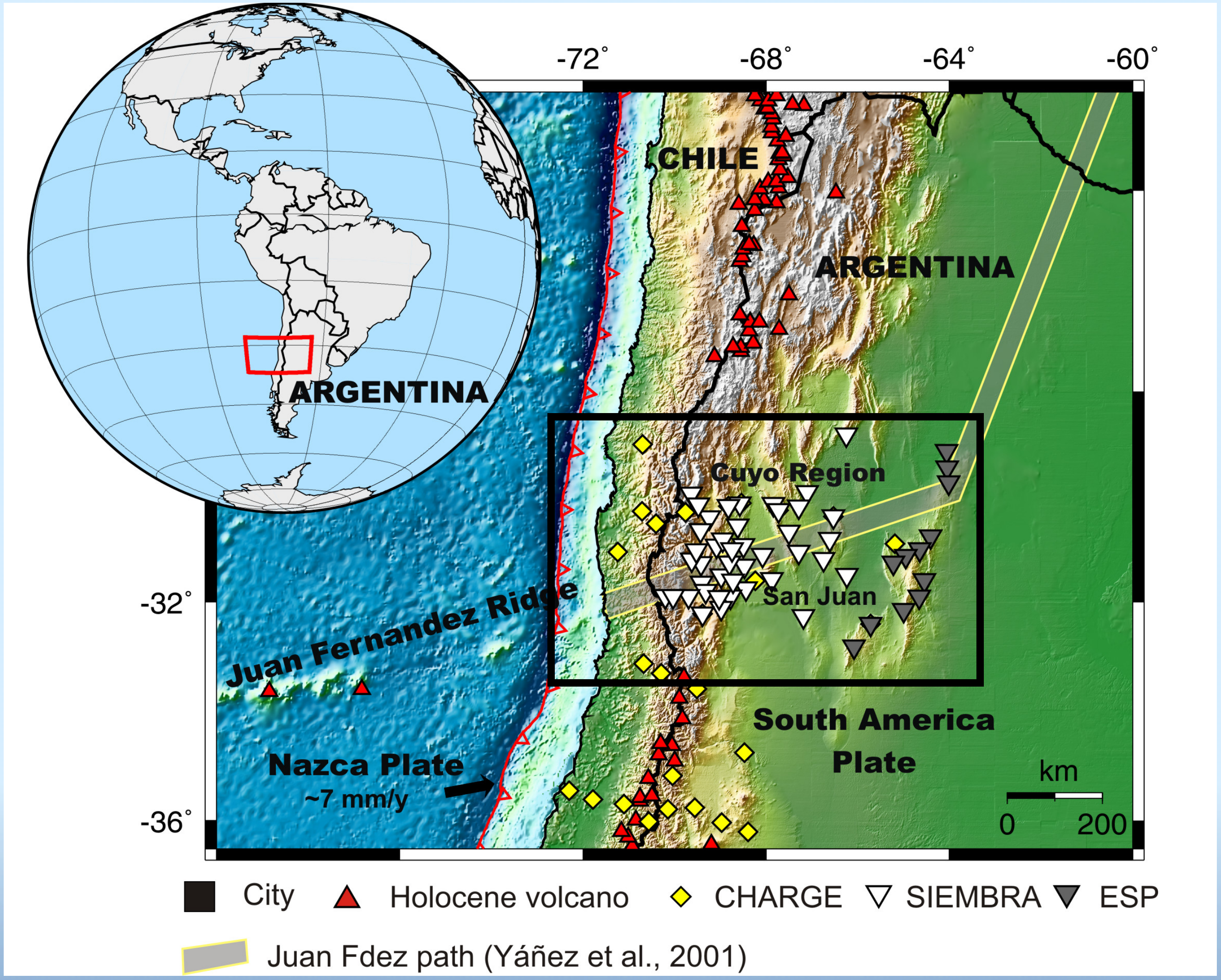
Flat Slab Subduction in South America

- *What is the role of subducted ridges in flat subduction?*
- *Are flat slabs strongly coupled to over-riding plate?*
- *Compare the Peru and Chile/ Argentina flat slabs*
    - *Argentina flat slab much more seismically active than Peru*
    - *Nazca Ridge much larger than Juan Fernandez Ridge*



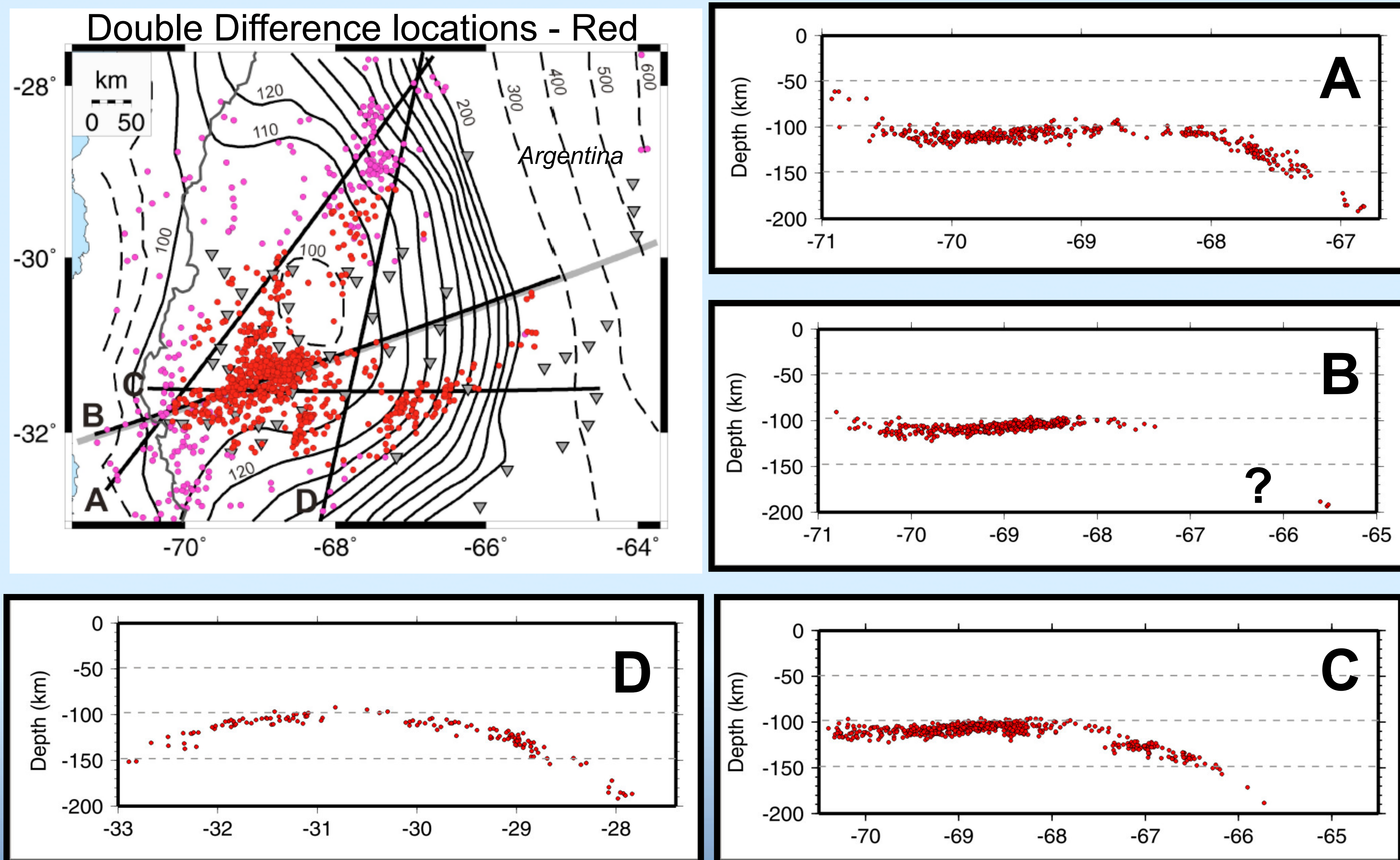
Improved Earthquake Locations

- *Subduction of the Juan Fernandez Ridge correlates with flat slab geometry*
- *Very high rate of seismicity in the down-going slab*
- *Active magmatic arc shut off ~6-8 Ma*
- *Site of the Sierras Pampeanas – active basement cored uplifts*



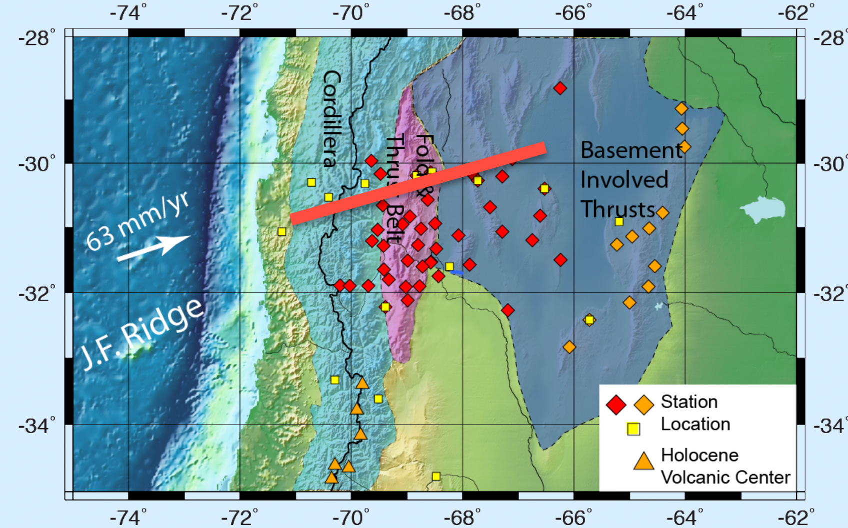
Linkimer et al. 2011

Earthquake Locations

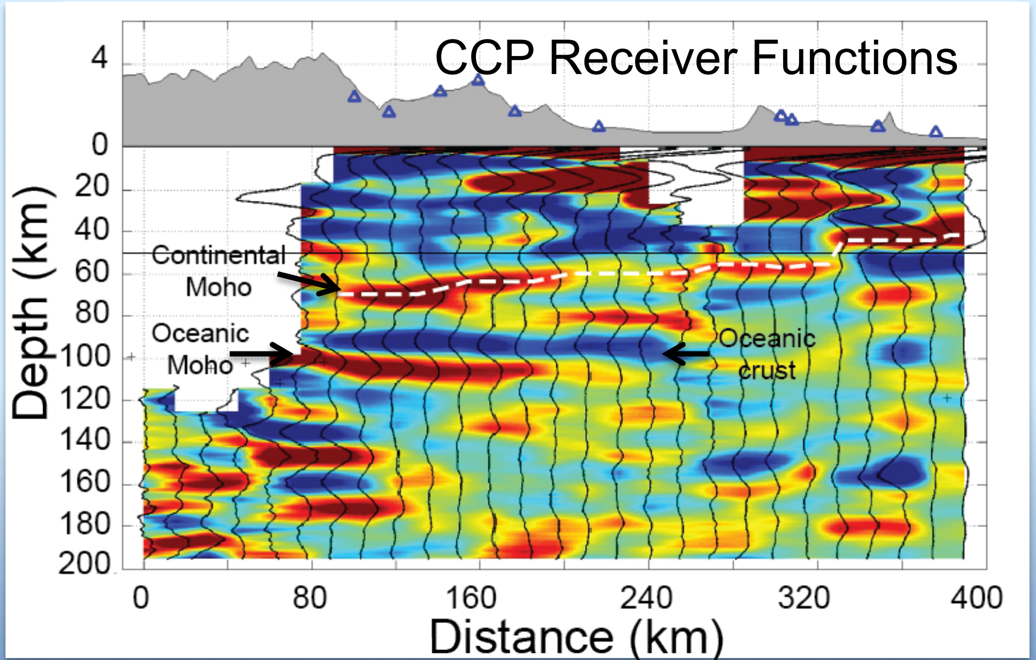


Linkimer, 2011

Common Conversion Point (CCP) Receiver Functions - Sierras Pampeanas, Argentina

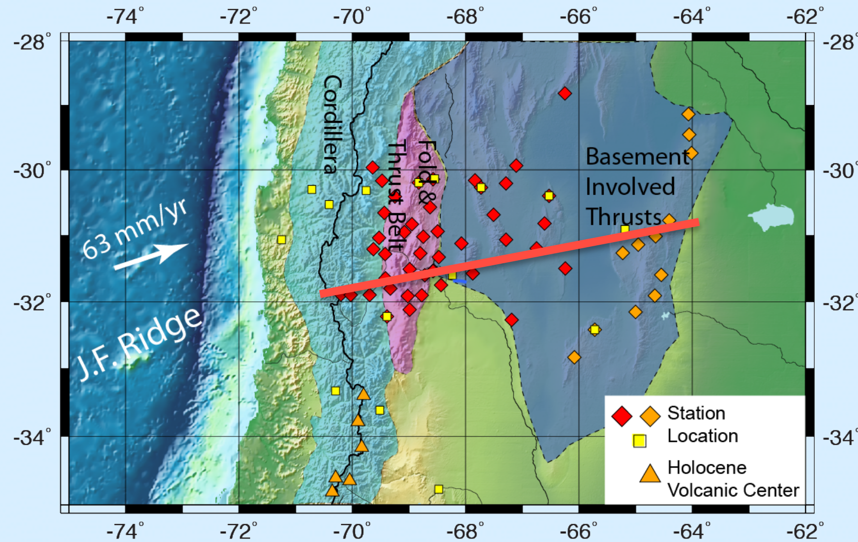


- *P-to-S conversions - Red is increase in velocity, blue is decrease in velocity with depth*
- *Flat slab is at ~100 km depth*
- *Top of the oceanic crust and the oceanic Moho are observed from converted phases*
- *Oceanic crust appears to end abruptly due to transformation to eclogite*



Gans et al., 2011

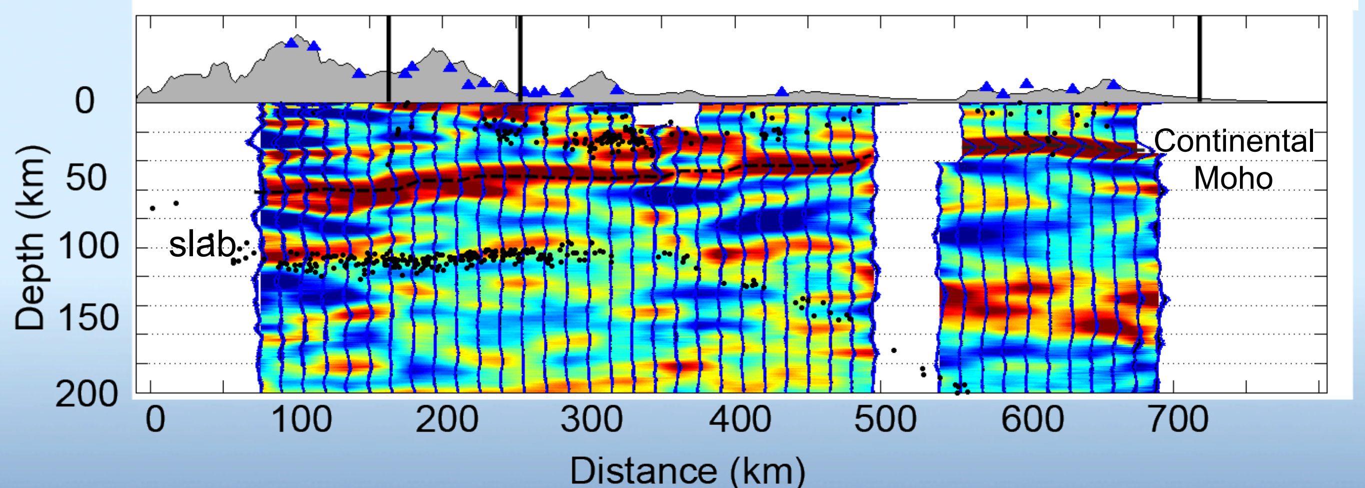
Common Conversion Point (CCP) Receiver Functions - Sierras Pampeanas, Argentina



- *Along the projected ridge axis the oceanic crust and Moho signals are not continuous*

- *Migrated with the shear velocity model from the ambient noise tomography*

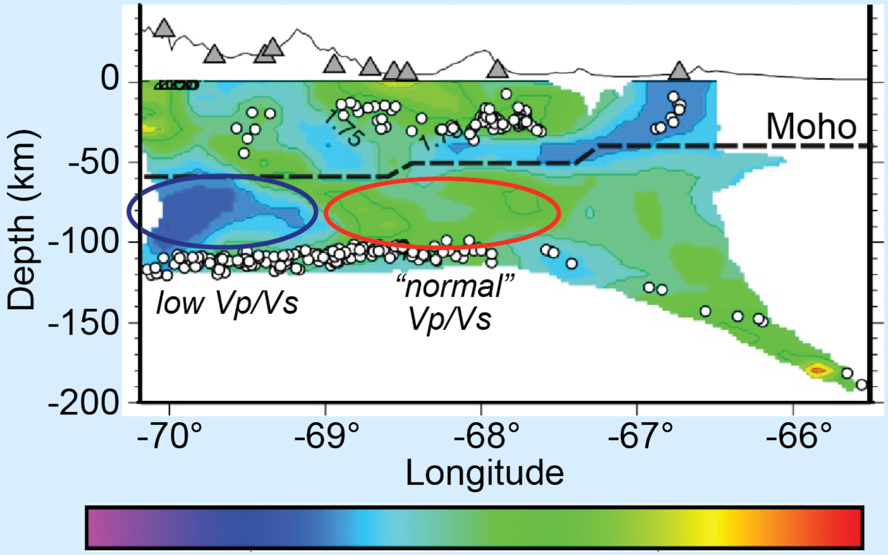
- *Strong P-to-S conversion from the continental Moho*



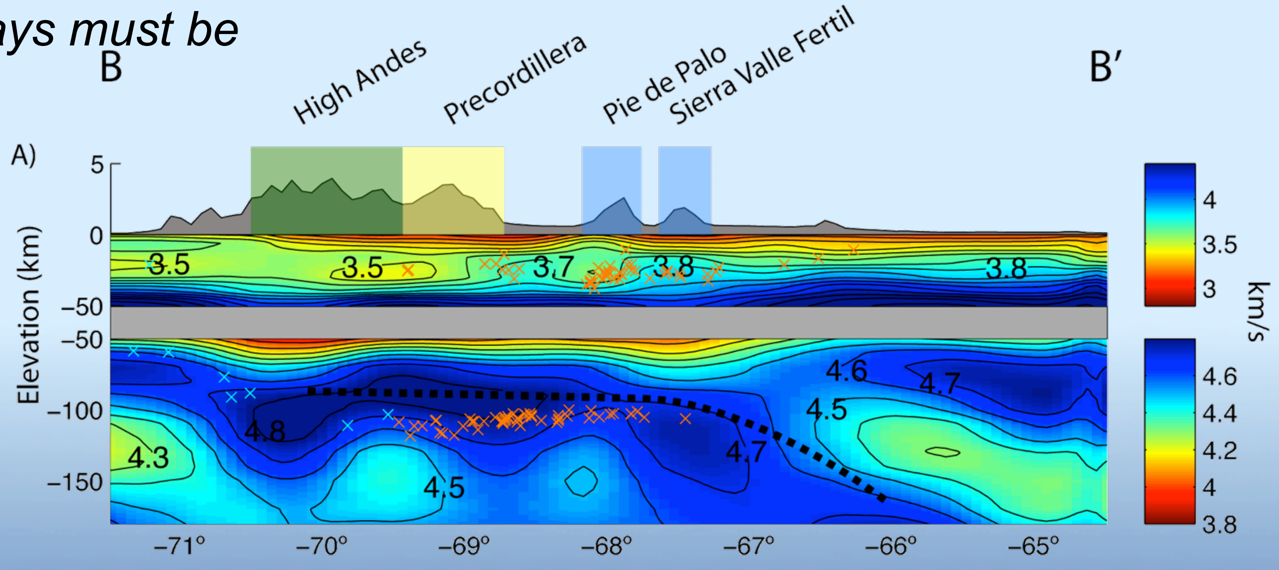
Bishop et al., 2015

Imaging the Argentina Flat Slab

- *Double difference tomography shows a region of low Vp/Vs and a region of "normal" Vp/Vs above the slab*
- *No evidence of large volume of hydrated mantle above the flat slab*
- *Suggests fluids pathways must be localized*
- *S-wave velocities from surface wave inversion shows the mantle above the flat slab is relatively fast until the slab begins to resubduct*



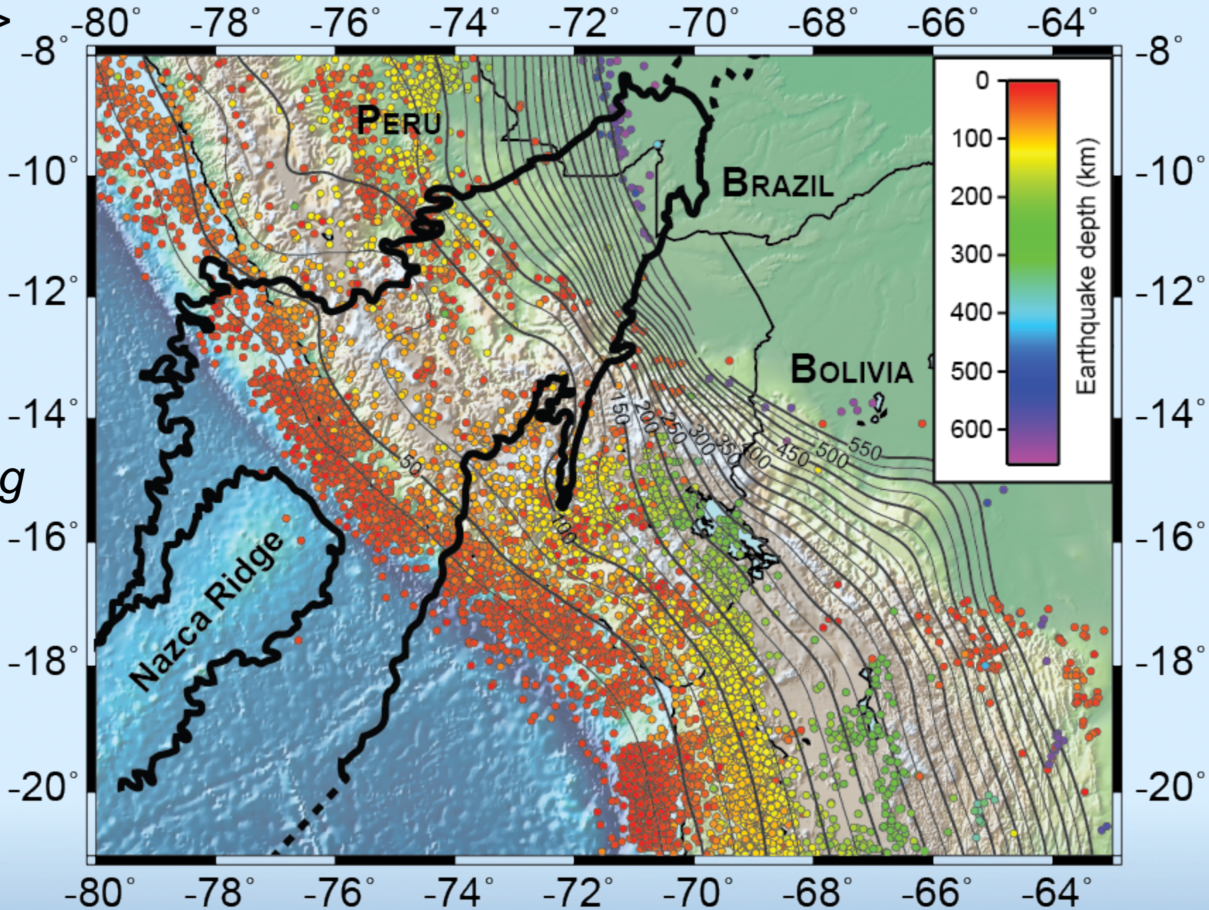
Linkimer, 2011



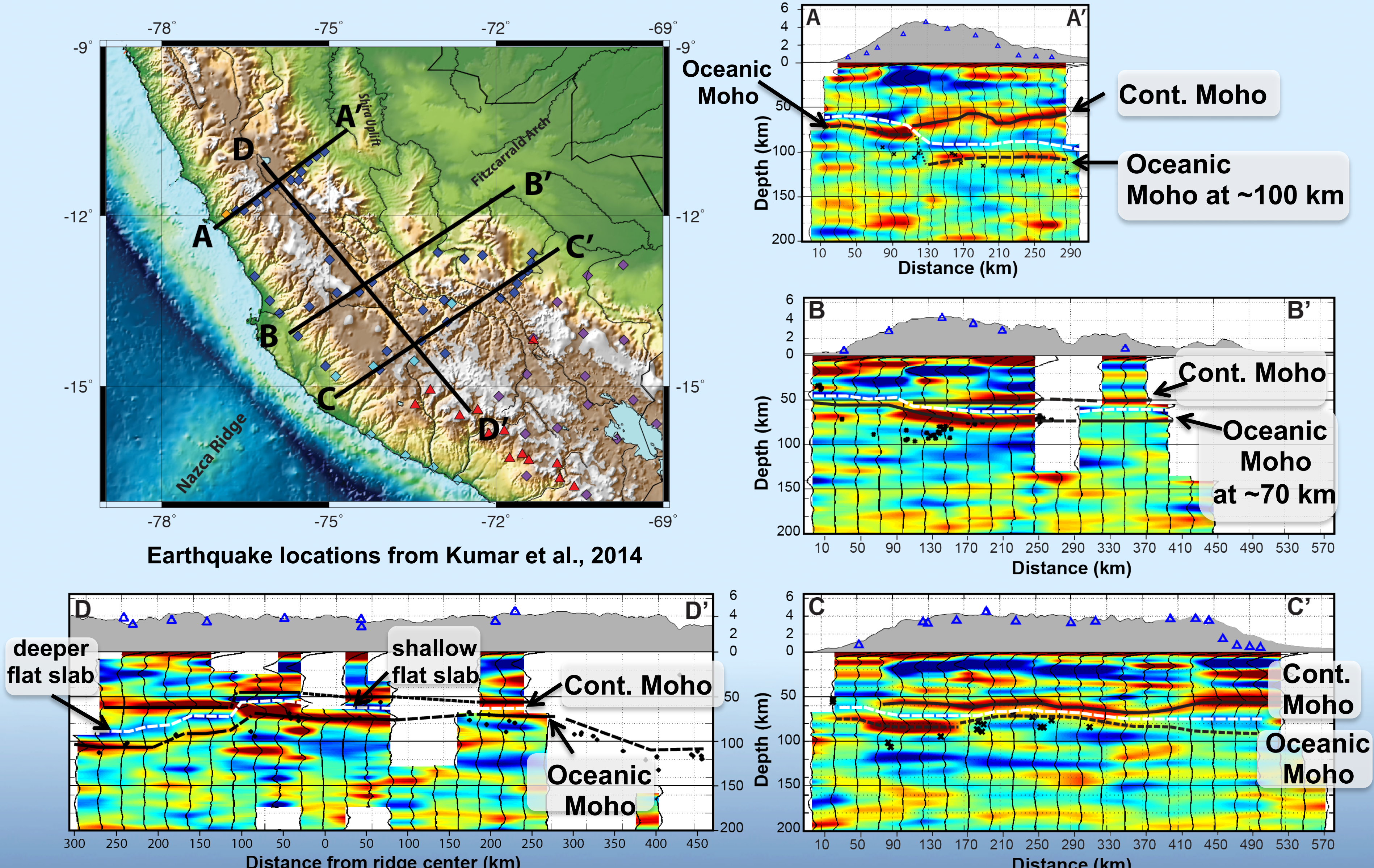
Porter et al., 2012

Peru Flat Slab

- *Map of seismicity (mag > 4) from NEIC*
- *Nazca slab depth contours from Slab1.0 model (Hayes et. al. 2012)*
- *Decreased number of earthquakes in slab along the ridge projection*
- *Projection of the Nazca Ridge (black) modified from Hampel (2002), based on the conjugate feature in the western Pacific, the Tuamotu Plateau*



CCP Receiver Functions

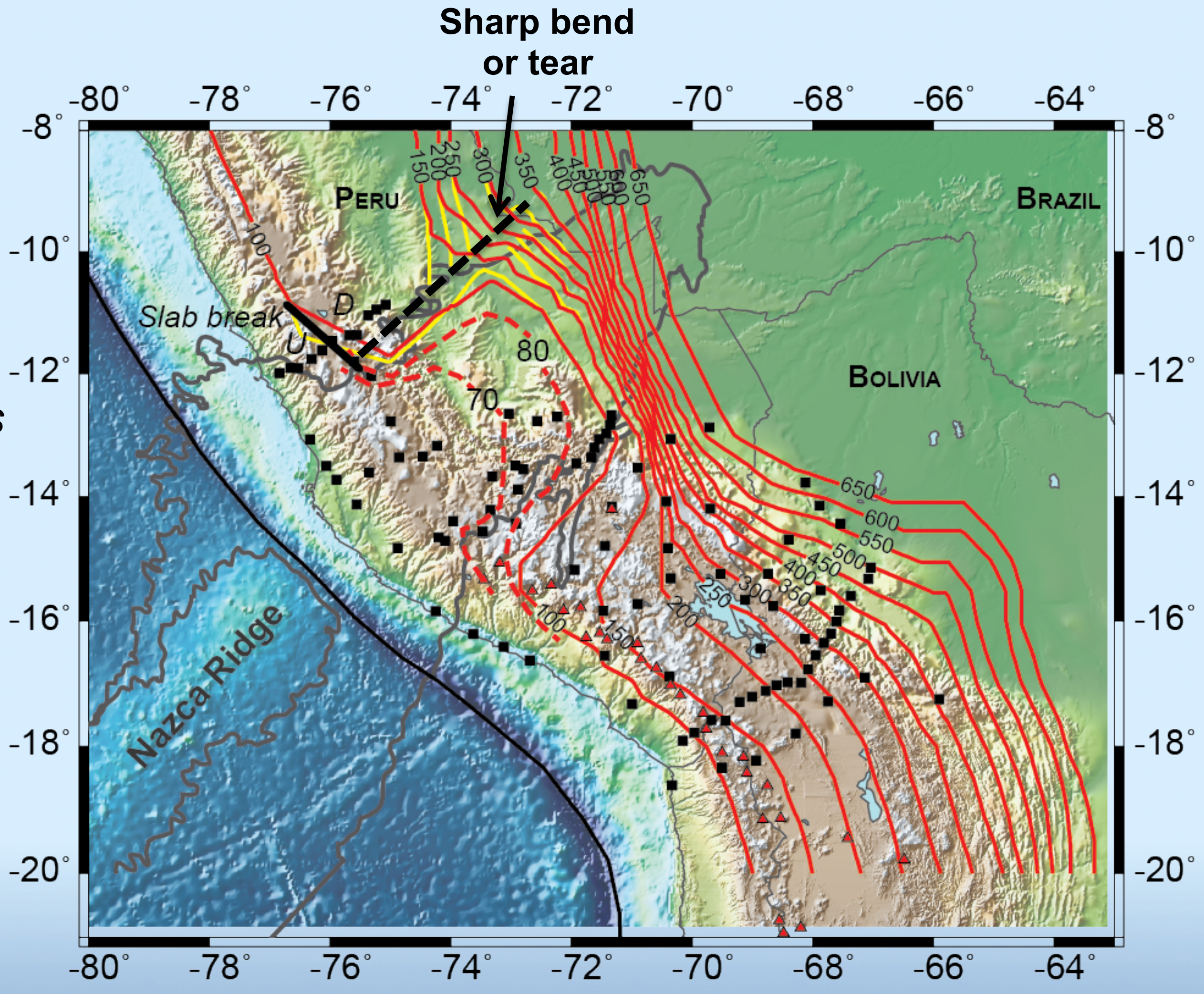


Earthquake locations from Kumar et al., 2014

Bishop et al., 2014

New Slab Contours

- *The slab oceanic Moho (based on RFs) shallows to <70 km where the Nazca Ridge subducts*
- *Coastal uplift as Nazca Ridge subducts*
- *Slab steepens to near vertical inboard of the Nazca Ridge subduction*
- *Sharp bend or tear along northern edge of the Nazca Ridge*
- *Suggests Nazca Ridge plays an important role in buoyancy of flat slab*



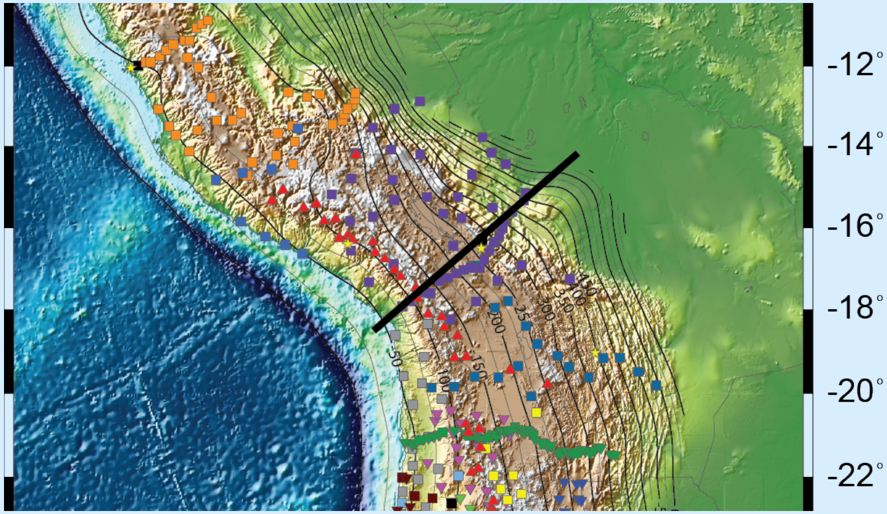
Scire et al., 2015
Bishop et al., 2015

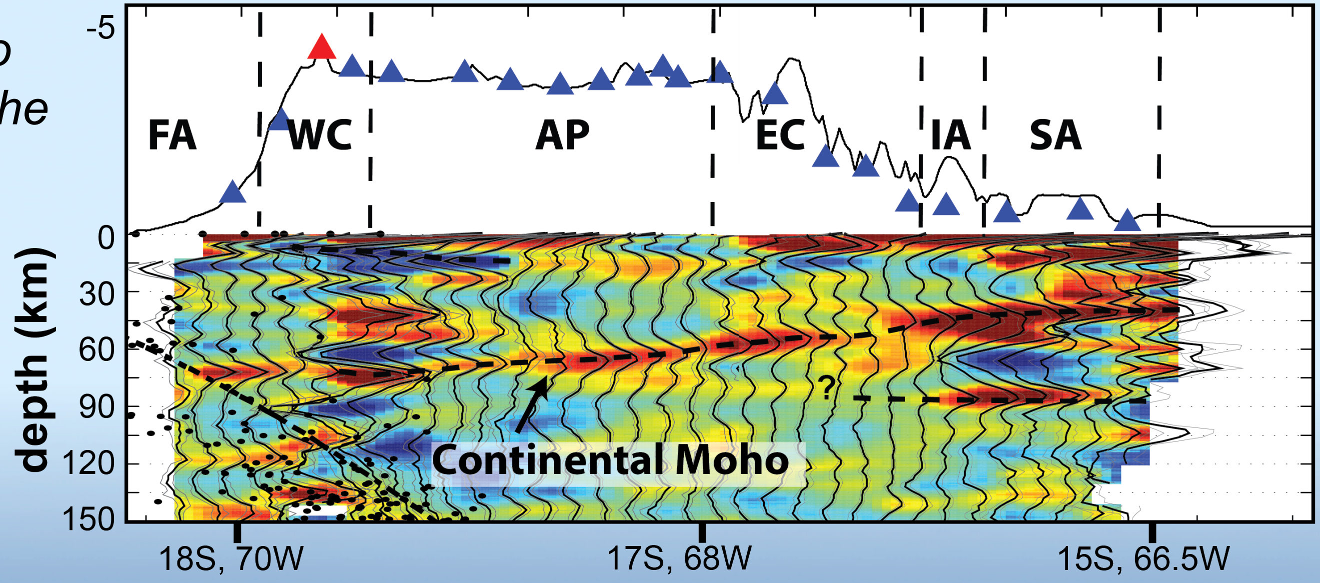
Flat Slab Subduction Summary

- *Both the Sierra Pampeanas and Peru flat slabs show indications of faulting where the ridges subduct*
- *Strongly coupled to the over-riding plate – suggests ridges play a role in flat slab subduction*
- *Differences*
  - *Peru flat slab flattens shallower and thins upper plate crust – more buoyant?*
  - *Sierras Pampeanas flat slab flattens deeper and seismicity is very high in slab and over-riding crust – less buoyant?*
  - *Buoyancy variation may reflect differences in the nature of the hotspot tracks*

Depth to Moho in the Central Andes

- *CCP receiver functions migrated with the ambient noise shear wave velocities*
- *Depth to the continental Moho 60-75km under the high elevations*

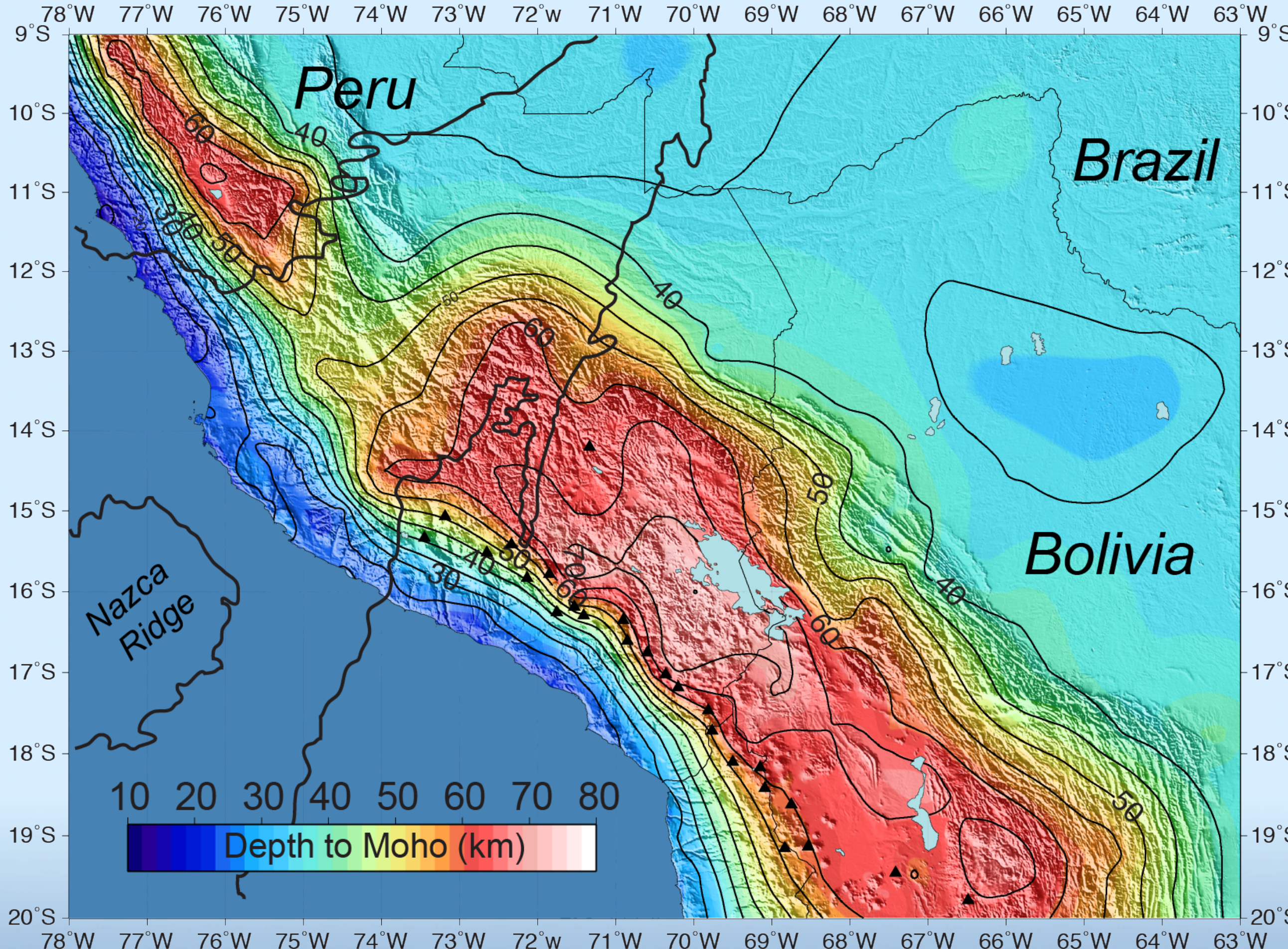




Ryan et al., 2015, in prep.

Depth to Moho – North Central Andes

- *Based on RFs and gravity (Tassara et al., 2006)*
- *Most of the high elevation of the Andean Plateau has a depth to Moho of 65-75 km*
- *Note disruption of thick crust along projection of Nazca Ridge*



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Summary

- *The high quality geophysical networks installed in Latin America will facilitate a major advancement in earthquake studies and seismic imaging (>350 stations in SA and ?? In Central America)*
- *Central & South American are ideal locations for a large scale international community projects*
- *Many people already working earthquakes & seismic imagining – how can we leverage what we are already doing and do it better?*
- *What type of community projects?*
  - *Seismogenic zone segmentation – along strike and up & down dip with Tsunami modeling*
  - *Improved earthquake locations - Double difference, locations with a 3D velocity models*
  - *Ambient Noise Tomography (crust)*
  - *Joint ANT Receiver Function inversions for improved crustal velocity models*
  - *Improved depth to Moho maps especially the forearc*
  - *Travel time tomography at regional and continent scales (0-1000 km)*
  - *Depth of the LAB map of South America*
  - *Other?*

Human Capacity Building Education & Training

- *We need more capacity building to support the new geophysical networks*
- *International graduate students at US institutions*
  - *Funded from research grants to US institutions*
  - *Funded by scholarships and fellowships from the country of origin*
- *Visiting scholars – short term visitors to US institutions*
  - *Funded by US research grants, Fulbright Fellowships, home institution, others?*
- *US visitors to international institutions*
  - *Funded by research grants, Fulbright Fellowships, host country?*
- *Advanced Studies Institutes – funded by NSF and organized by IRIS, duration from 2 days to 2 weeks*