Receiver Function Studies in Southern Peru

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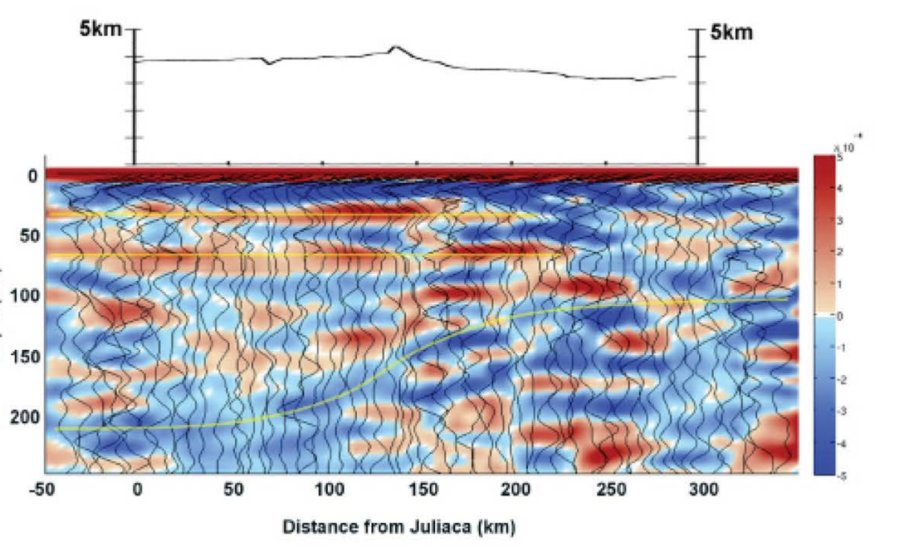
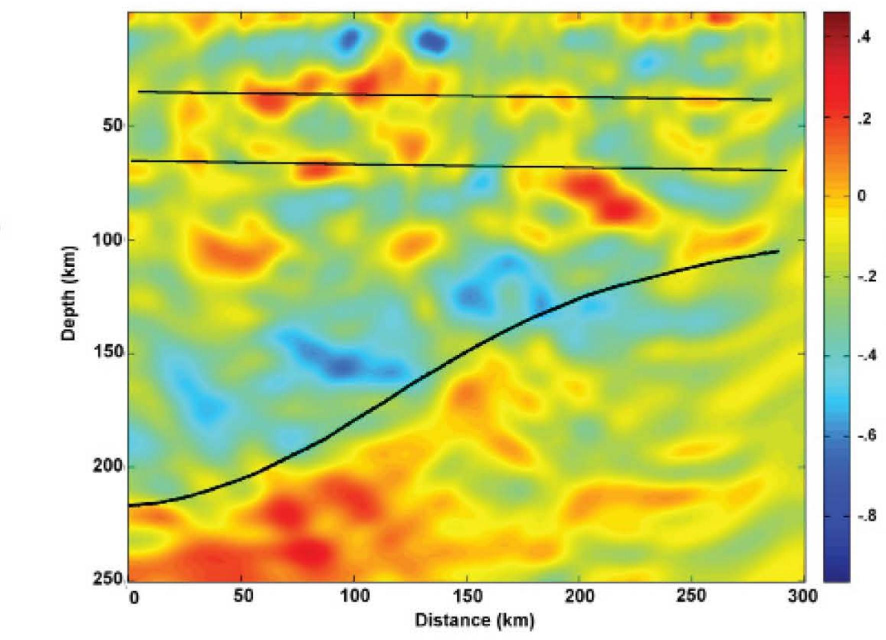
Abstract

Southern Peru represents a transition from flat slab subduction in central Peru where the Nazca plate subducts almost horizontally beneath South America, to normal subduction with a ~30 degree dip angle in southern Peru/northern Chile. Three broadband seismic arrays were installed in Southern Peru to analyze the structure of the subduction system and the nature of the transition from normal to flat slab subduction. Line 1, running perpendicular to the trench from Mollendo to Juliaca, samples the normal subduction region. Line 2, running parallel to the ocean trench from Juliaca to Cusco, samples the transition from normal to flat slab subduction. Line 3, perpendicular to the trench from Nazca to Cusco, samples the flat subduction region near where the Nazca Ridge is subducting. Each array has a distance of at least 300 km (except for Line 3 which is 400 km with an additional 100 km covered by several stations added from the PULSE experiment) and has 50 stations allowing for nominal coverage of one station every 6 km. Half of the stations from the first two arrays were relocated several years into the experiment to form the third array. Teleseismic and local data was utilized to make receiver functions using the P wave phase in addition to other phases such as PP, PKP, and S/SKS. Resulting receiver function results provide high quality imaging of the subduction system directly beneath the arrays. The shape of the slab was observed in the regions of normal subduction, the transition from normal to flat slab subduction, and the region of flat slab subduction. In addition to clarifying the shape of the slab, the Moho depth was observed to reach a maximum depth of about 70-75 km beneath the Altiplano. Receiver function images also show a positive impedance mid-crustal signal at 40 km indicating a velocity increase which is suggested to be a possible observation of the under-thrusting Brazilian Shield. Crustal signals which are less defined by teleseismic receiver functions can be clarified by looking at local receiver functions from deep events close to the arrays. Receiver functions for individual stations can be stacked to obtain estimates of Moho depth and Vp/Vs ratio. The average Vp/Vs ratio for the region was found to be around 1.75 with a few regions of elevated Vp/Vs near the active volcanic arc. Although most of the receiver function results come from an analysis of radial receiver functions, observations of energy on transverse receiver functions can provide information about dipping structure or anisotropy. Receiver function results provide a simple way of making direct observations of key structural interfaces and the current state of the subduction system which has relevance in studies of the tectonic evolution of the region and estimations of causes of flat slab subduction.

Line 2 (Subduction transition)

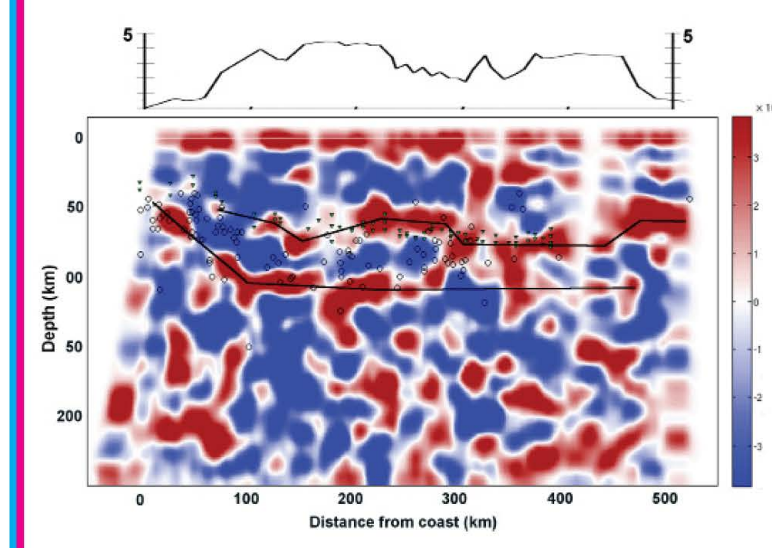


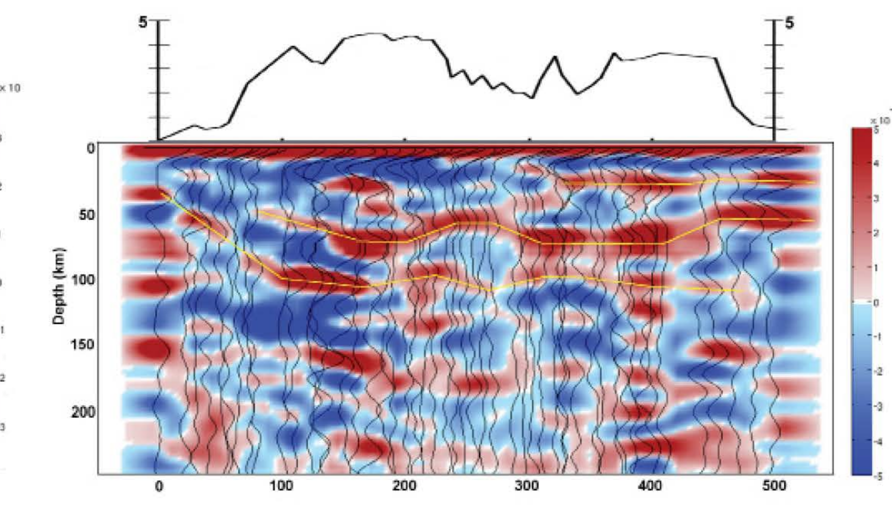


Top left: Receiver function image from Line 2 covering the transition from normal to flat slab subduction. The line runs from Juliaca to Cusco. The above image was formed by plotting common conversion point (CCP) stacks with a bin spacing equal to station spacing. A clear mid-crustal structure and Moho signal are observed. The slab signal appears primarily as a negative signal. The positive signal above it also appears associated with the slab. The transition is believed to be a bend rather than a break in the slab.

Top right: Image from migration of receiver functions for Line 1. There is a transition from negative to positive impedance observable near the expected location of the slab

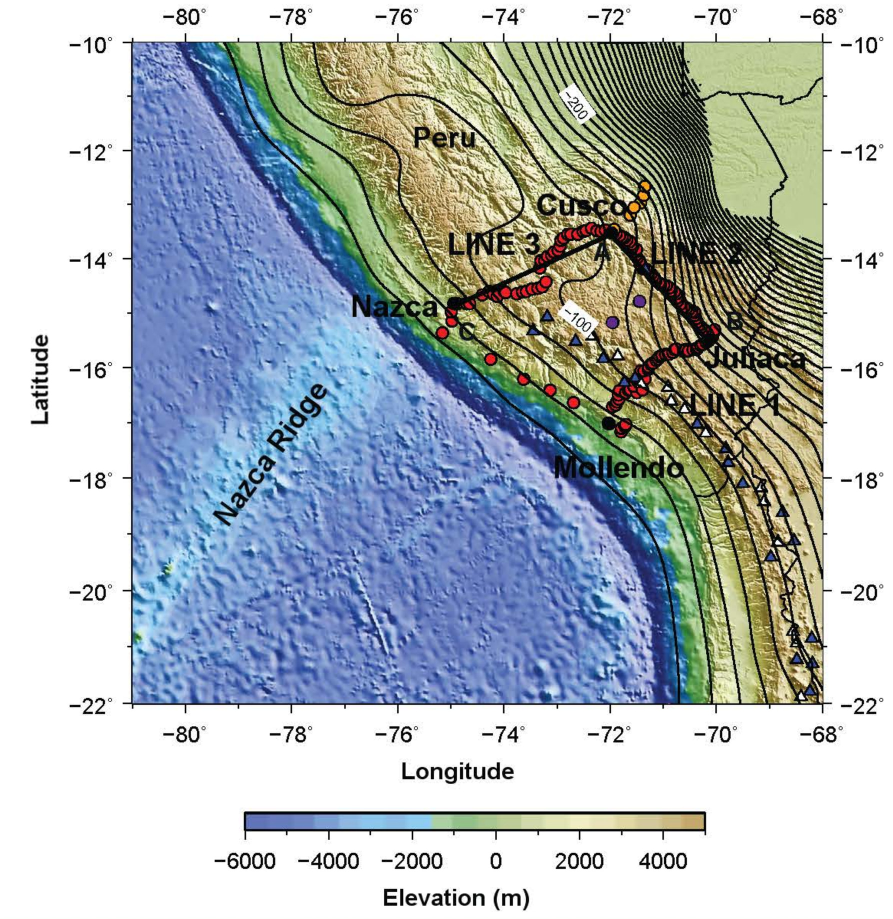
Line 3 (Flat slab subduction)

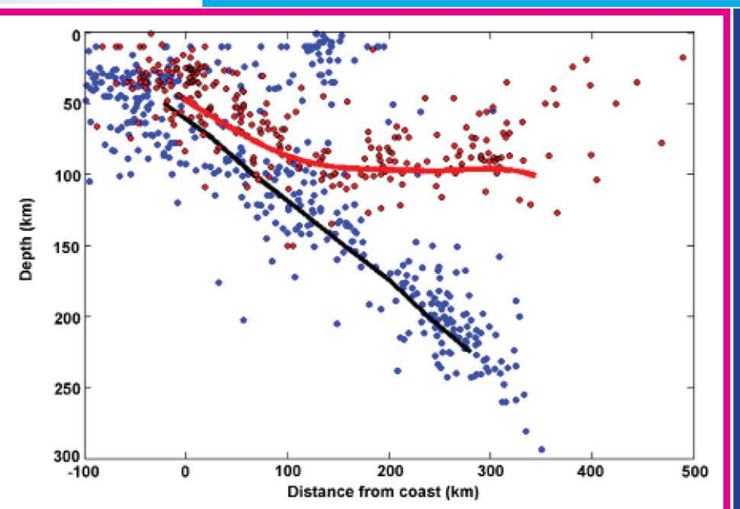




Receiver function images from Line 3 located in the flat slab region near where the Nazca Ridge is subducting show the Nazca plate flattening out at around 100km beneath the Altiplano. The Moho signal and a shallower mid-crustal signal are also observed. The Moho depth is observed to follow the topography and is roughly consistent with Airy isostatic compensation beneath the Altiplano.

The top left image is formed from a backprojection of receiver functions from a northwest azimuth while the top right image shows the amplitude of CCP (common conversion point) stacks for each distance bin. Distance runs from the coast near Nazca to Cusco perpendicular to the trench. Both images show consistent results for the major interfaces. The results from 400 to 500km come from 5 stations from the PULSE experiment which were added to the arrays.

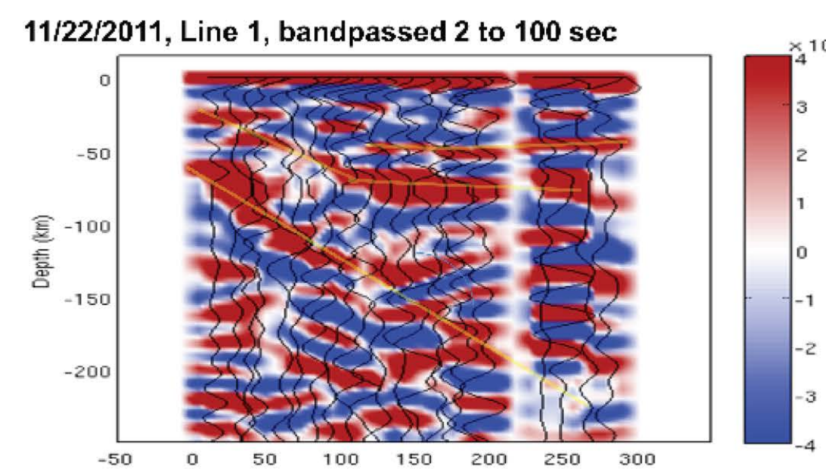




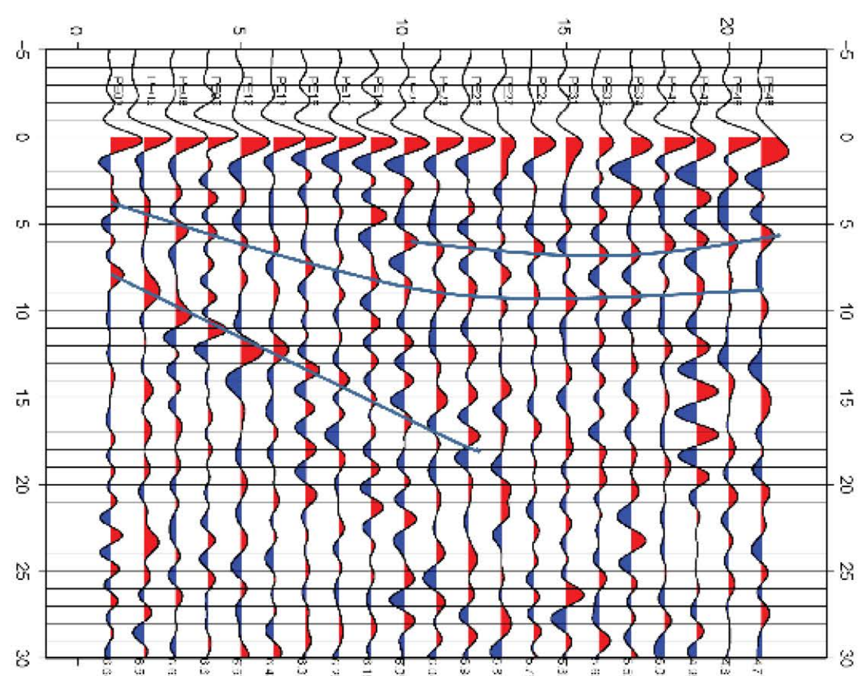
Right: Topography and bathymetry map of Peru with slab contours from the Slab 1.0 model (Hayes et al, 2012). Seismic arrays installed in Southern Peru are represented by red circles. Line 1 is located in the region of steeper subduction dip angle, Line 2 represents the transition to flat slab subduction, and Line 3 is located in the flat slab region. Orange circles are added stations from the PULSE experiment and purple circles are added stations from the CAUGHT project. Blue and white triangles are dormant and active volcanoes. Note that the active volcanic arc is located in the region of normal subduction while there is a volcanic gap in the region of flat slab subduction.

Above: A comparison of seismicity in the normal and flat slab regions with locations from the NEIC earthquake catalog for earthquakes from 1982 to present with magnitudes greater than 4.0.

Local Receiver Functions



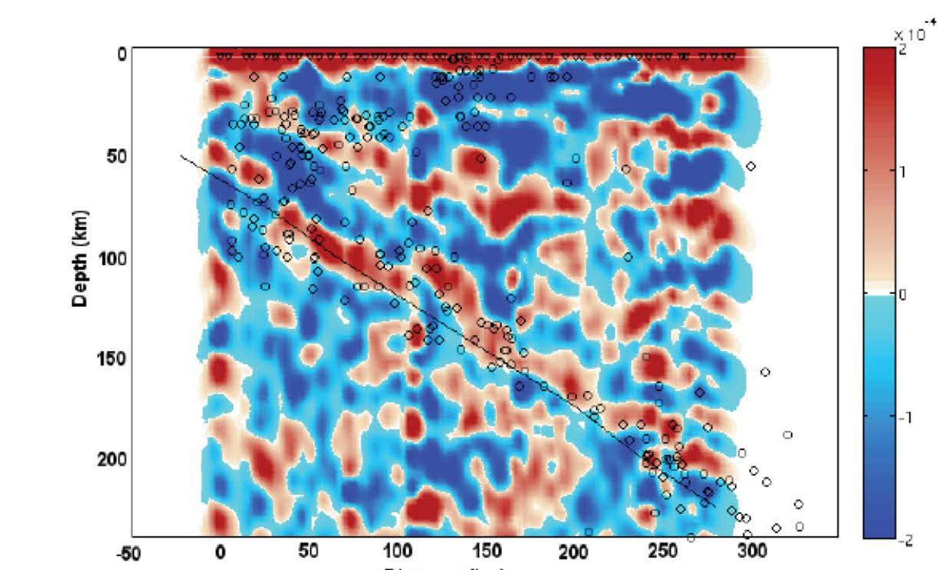
Receiver functions were made with local events to clarify smaller scale crustal features which may not be as clear in teleseismic RFs. Events were considered if they were close to the arrays and had a depth greater than about 180 km to avoid crustal interference. A sample local receiver function is shown to the right for Line 1. The earthquake is a magnitude 6.6 event at round 556 km depth which occurred due east of Juliaca on 2011/11/22.



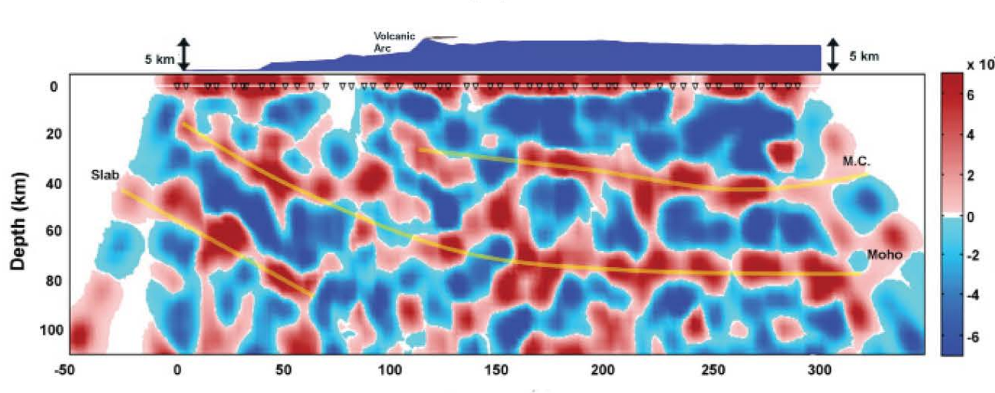
Top left: Plot of the receiver function traces for Line 1 as a function of depth where each receiver function is centered on the station distance. Distance is the distance from Mollendo on the coast. The signal from the Moho is clear as is the mid-crustal structure at about 40km depth. Structure is not resolvable at depths greater than around 125 due to lack of sampling by the local event.

Bottom left: Receiver function traces included in the image above as a function of time.

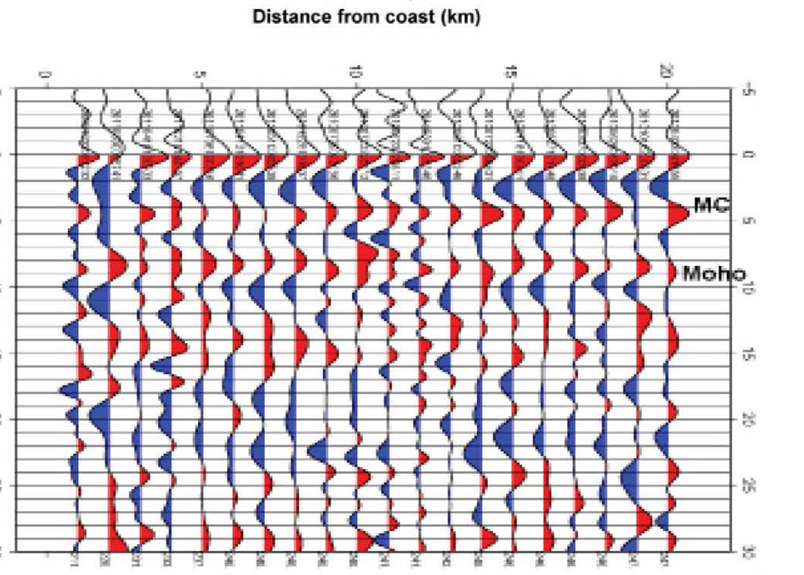
Line 1 (Normal Subduction)



Top right: Receiver function image for Line 1 based on a plot of CCP (common conversion point) stacks. Receiver functions are first backprojected as rays in the direction from which the energy originated from. The distance and depth at which the receiver function ray intercepts the polynomial line which best fits the Moho depth estimates determine the bin in which the receiver function is placed. The bin size in this case is proportional to station spacing. The receiver functions in each bin are stacked and the stacks are plotted as shown to the right. The Moho can be seen dipping from about 30 km near the coast to about 75 km depth beneath the Altiplano. There is also a mid-crustal signal at 40 km depth suggested to be the under-thrusting of the Brazilian Shield beneath the eastern portion of Peru. A positive signal from the slab can be seen dipping at an angle of about 30 degrees consistent with seismicity in the Wadati Benioff zone.

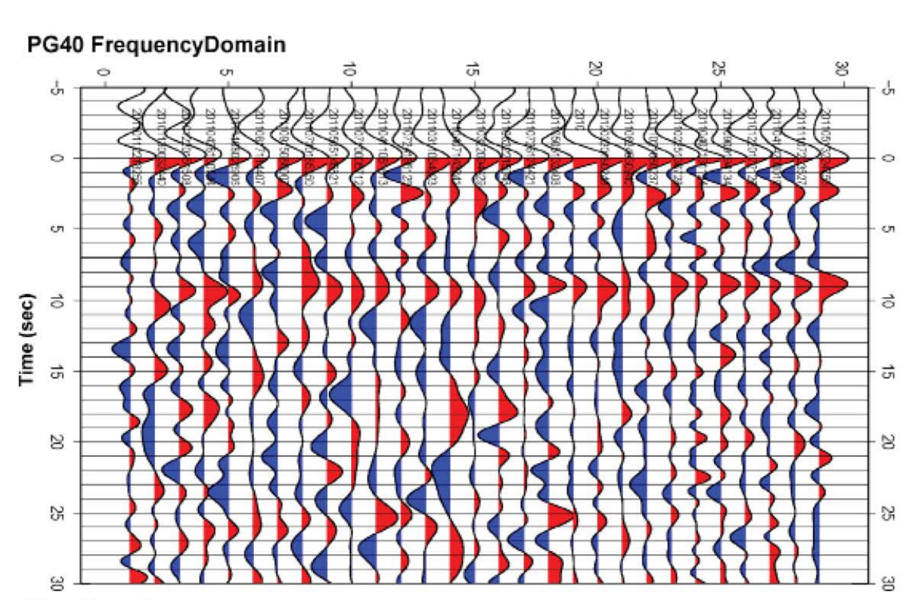


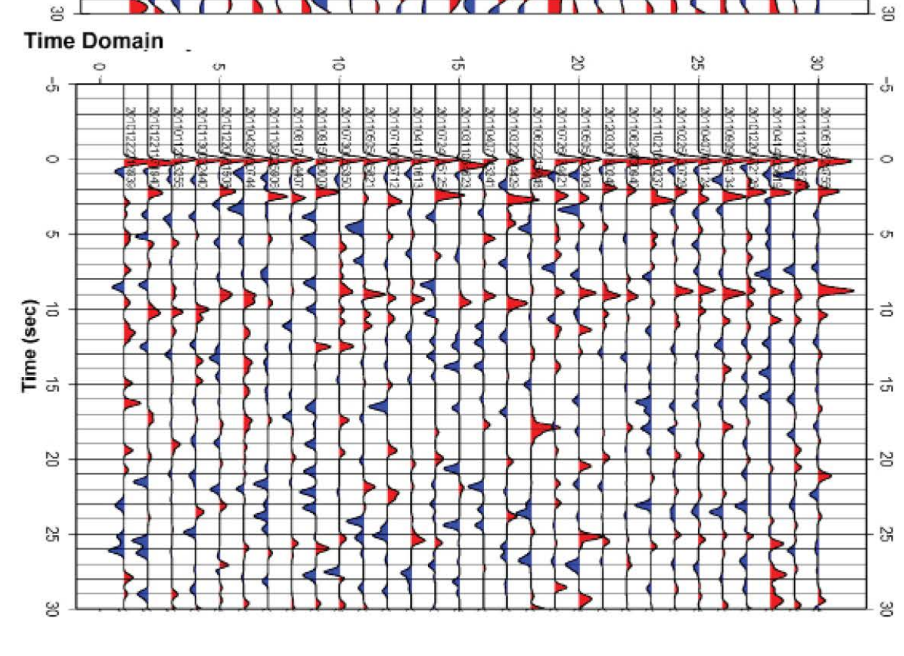
Receiver function image from Line 1 from a backprojection of rays from all azimuthal directions. This image zooms in on the upper 120 km showing a clear signal from the Moho and mid-crustal structure and the start of the subducting Nazca plate marked by yellow lines.

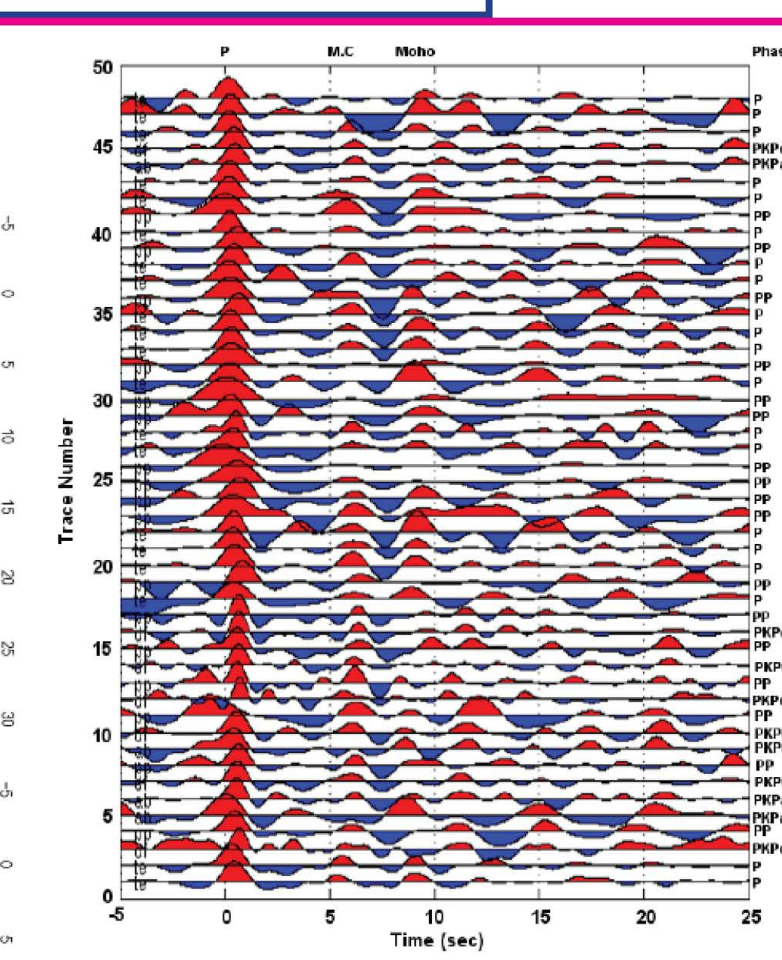


Receiver functions from an individual station near Juliaca showing consistent signals from the mid-crustal structure at about 4-5 seconds (~40 km depth) and a Moho signal at about 9 seconds (close to 70 km depth). Both signals are positive impedance indicating a velocity increase at the interface. A similar signal is consistent throughout stations on the eastern portions of the arrays, particularly for Line 2 where the mid-crustal structure is seen as a flat signal at 40 km depth. Several authors have supported the idea that the mid-crustal structure is underthrusting at least as far as the Eastern Cordillera (McQuarrie et al., 2005; Gubbels et al., 1993; Lamb & Hoke, 1997; Beck & Zandt, 2002). We suggest that the Brazilian Shield could underthrust a bit farther undernear Southern Peru, possibly underplating part of the Altiplano. This would have implications for the timing of uplift

Receiver Function Methods





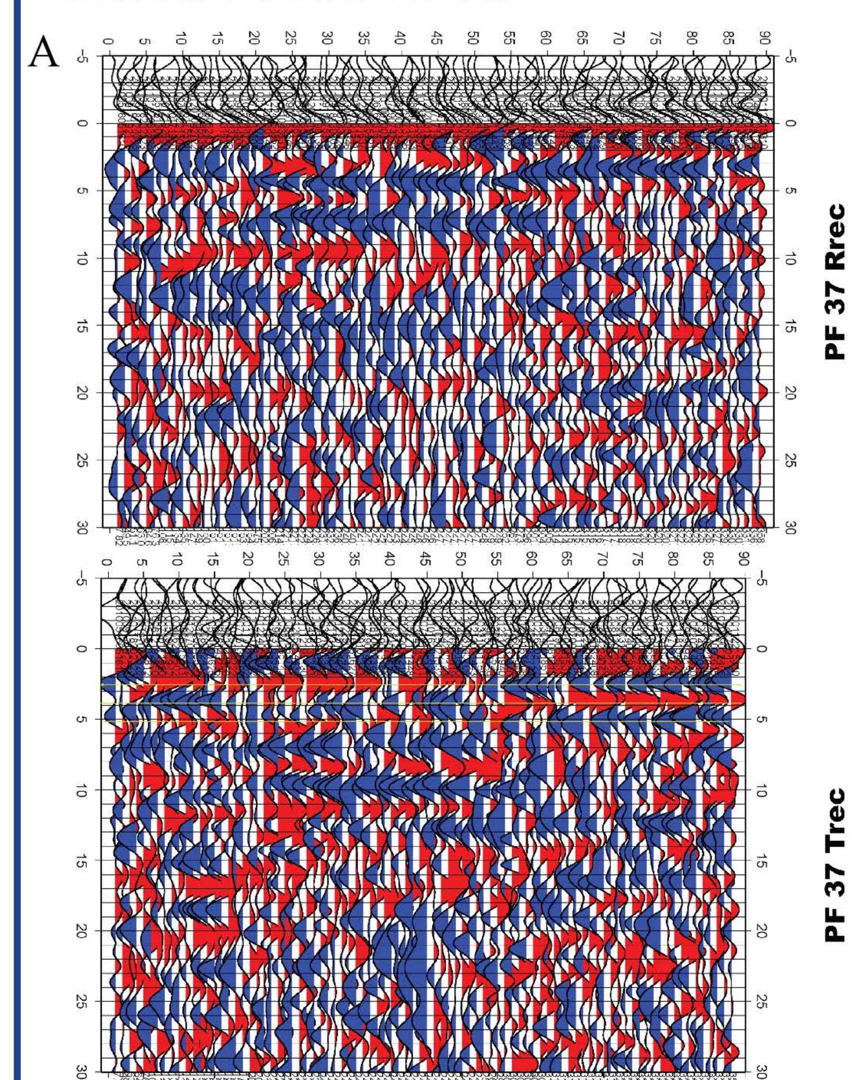


Left: Comparison of receiver functions from a NW azimuth for station PG40 using frequency domain deconvolution (top) and time domain deconvoltution (bottom). Major arrivals are seen to be consistent for both methods.

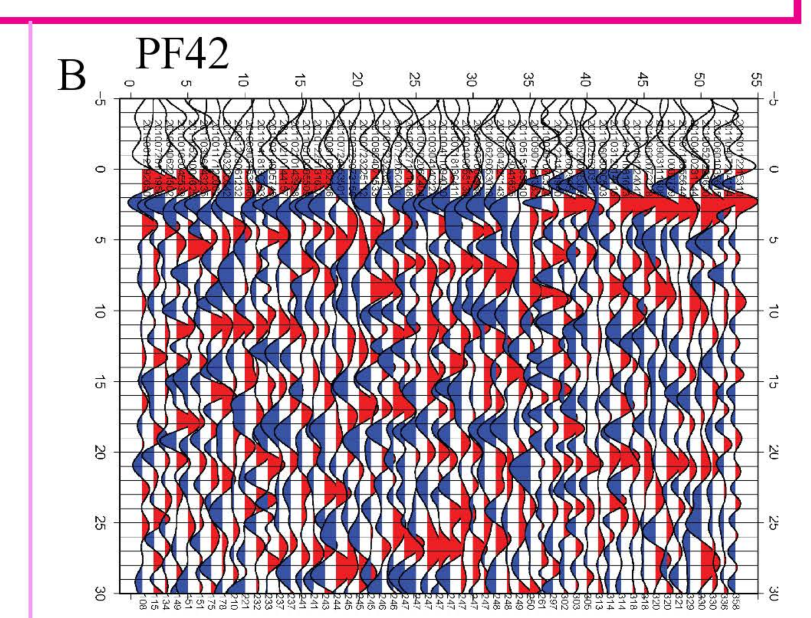
Top: Receiver functions for station PE46 with events from a NW azimuth including all P-wave phases used for receiver functions (P,PP, PKPab, and PKPdf). Arrivals are seen to be generally consistent for the mid-crustal structure at about 6 seconds and Moho signal at about 9 seconds. However for analysis P and PP receiver functions are separated from PKP receiver functions. Due to the almost vertical arrival angle of PKP waves, no conversion is generally expected at horizontal interfaces but the PKP phase can be useful for detecting dipping structure such as the 30 degree dipping slab in the normal subduction region.

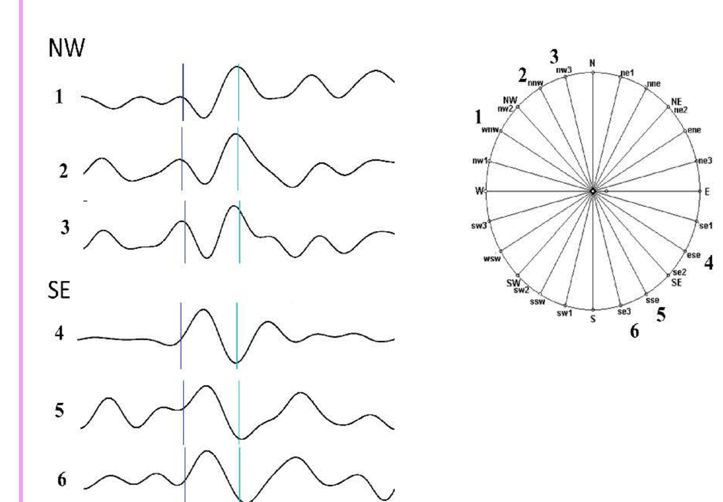
Transverse RFs

A

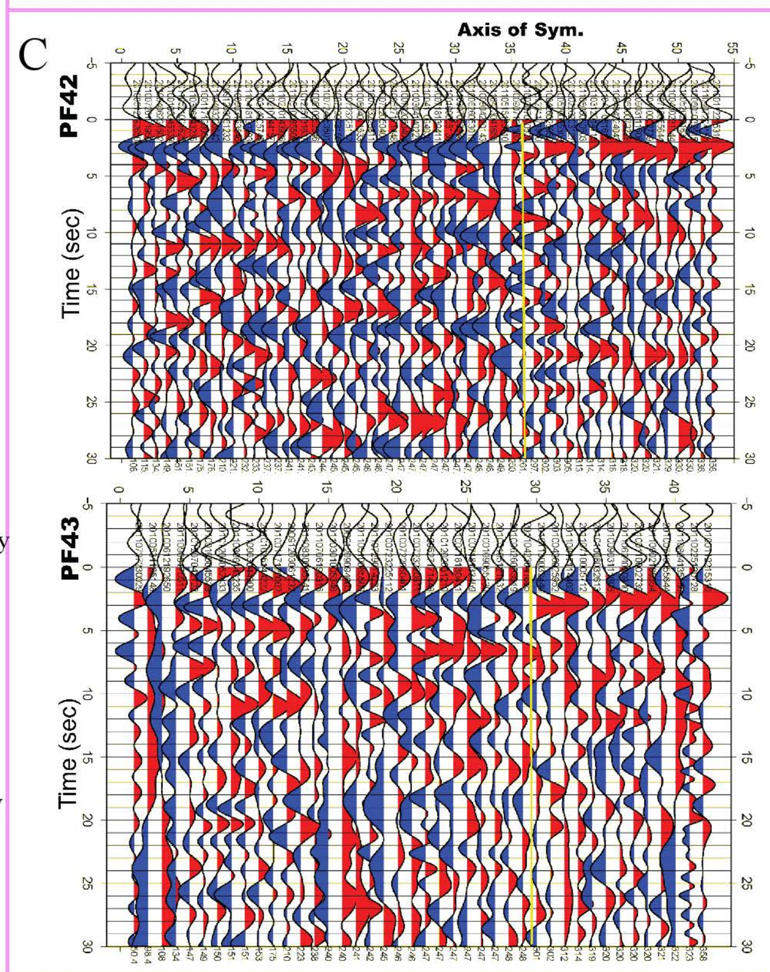


B





C



In the case of a flat, homogeneous crust, transverse receiver functions are expected to have very little energy relative to radial receiver functions. However in many cases, the amplitude of signals of signals observed on the transverse component is comparable to those of the radial component. An analysis of the transverse component can be useful for studying anisotropy or dipping structure.

A) Comparison of radial and transverse receiver functions for station PF37 (from all available azimuths). Note the coherent signals on the transverse RFs which have an amplitude similar to the radial component.

B) According to Savage, (1998), transverse RFs have a 180 degree periodicity in cases of transversely anisotropic regions with a horizontal symmetry axis and 360 degree periodicity for a dipping symmetry axis or dipping structure. By comparing trasnverse RFs from 180 degrees apart in backazimuth, we can make an estimate of which is the case here. In almost all stations, at the time of major arrivals in the transverse component, traces 180 degrees apart (eg NE vs. SW or NW vs. SE) are found to have opposite polarity indicating possible anisotropy

C) An estimate for the symmetry axis is marked for stations PF42 and stations PF43

References

Phillips, K. E., R. Clayton, P. M. Davis, H. Tavera, R. Guy, S. Skinner, I. Stubailo, L. Audin, and V. Aguilar, Structure of the Subduction System in Southern Peru From Seismic Array Data, J. Geophys. Res.,doi:10.1029/2012JB009540, in press.

Phillips, K.E., & R.W. Clayton, Structure of the Subduction Transition Region from Seismic Array Data in Southern Peru, Submitted to *Geophysic. J. Int.*

Hayes, G.P., Wald, D.J. & Johnson, R.L., 2012. Slab1.0: A three-dimensional model of global subduction zone geometries, *J. Geophys. Res.*, 117, B01302

Beck, S., and G. Zandt (2002), The nature of orogenic crust in the Central Andes, Journal of Geophysical Research, 107, 2230.

Gubbels, T., B. Isacks, and E. Farrar (1993), High-level surfaces, plateau uplift, and foreland development, Bolivian central Andes, Geology, 21, 695–698.

Lamb, S., and L. Hoke (1997), Origin of the high plateau in the Central Andes, Bolivia, South America, Tectonics, 16 (4), 623–649.

McQuarrie, N., B. Horton, G. Zandt, S. Beck, and P. DeCelles (2005), Lithospheric evolution of the Andean fold-thrust belt, Bolivia, and the origin of the central Andean plateau, Tectonophysics, 399, 15–37.

Savage, M. (1998), Lower crustal anisotropy or dipping boundaries? Effects on receiver functions and a case study in New Zealand, Journal of Geophysical Research, 103, B7, 15,069-15,087

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