Using seismic methods to determine the crustal structure of the Aleutian Island Arc

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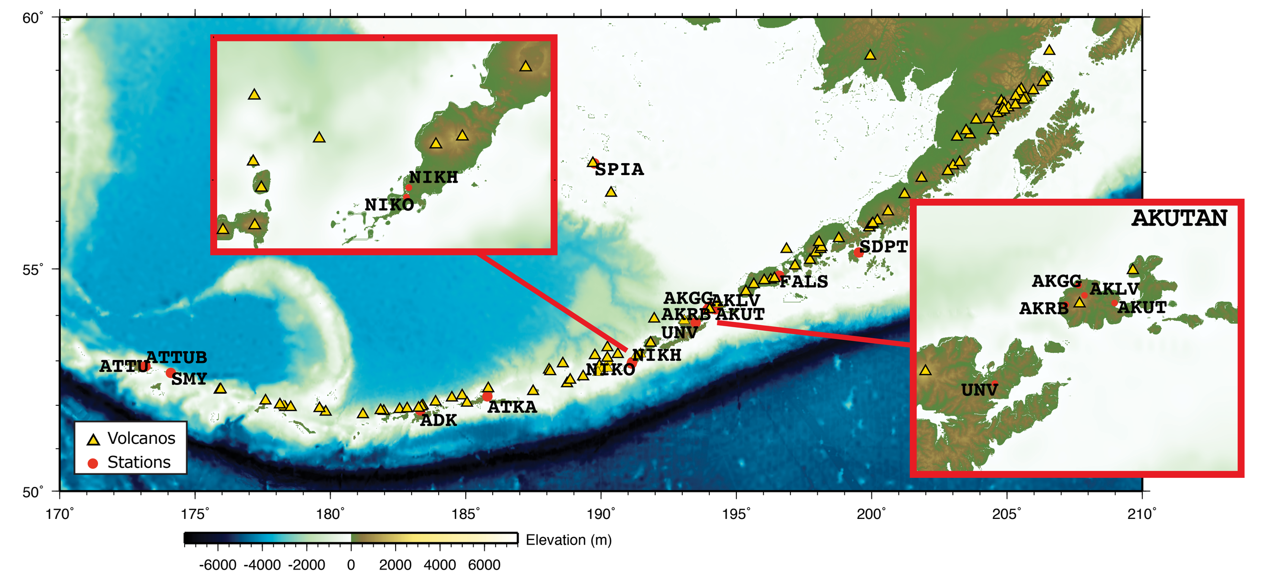
Introduction

Subduction zones and their associated island arcs are sites of continental crust production. Weight percents of silica oxide differ between island arc magmas and the average continental crust. Removal of denser, more mafic material from the island arcs would push their composition closer to that of the continental crust. Differentiated magmas and delamination provide a mechanism for this removal (Rudnick, 1995; Behn and Kelemen, 2006).

Studying island arcs is limited to geochemical studies of the erupted lavas and remote geophysical studies. The Aleutians in Alaska are well studied from both the geochemical and geophysical perspective. Most geophysical studies have utilized active source seismic data (ie. Shillington et al., 2004). Fundamental questions still remain pertaining to the composition of the lower crust. This study uses passive source seismic data, which can help determine the validity of the structure from previous active source seismic studies, as well as put better constraints on the composition of the lower crust.



Map showing the locations of the seismic stations and the volcanos in the Aleutian Islands. We collected earthquake data from January 2000 - December 2008, though many of these stations were in operation for only part of that time period.

Methods

Fifteen seismic stations in the Aleutians collected data from earthquakes that were between 5.0 and 7.0 in magnitude and occured from 25° to 90° away. Receiver functions were used to determine the crustal structure. Vertical, north, and east directions are recorded for each earthquake. North and east are rotated to the radial and transverse directions (parallel and perpendicular to the direction of P wave propogation respectively).

The recorded seismic wave is a convolution of three components: the source, the structure, and the instrument response. A deconvolution in the time domain isolates the structure component. This isolated structure component is the receiver function.

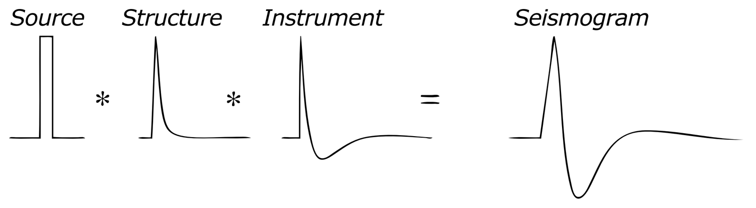
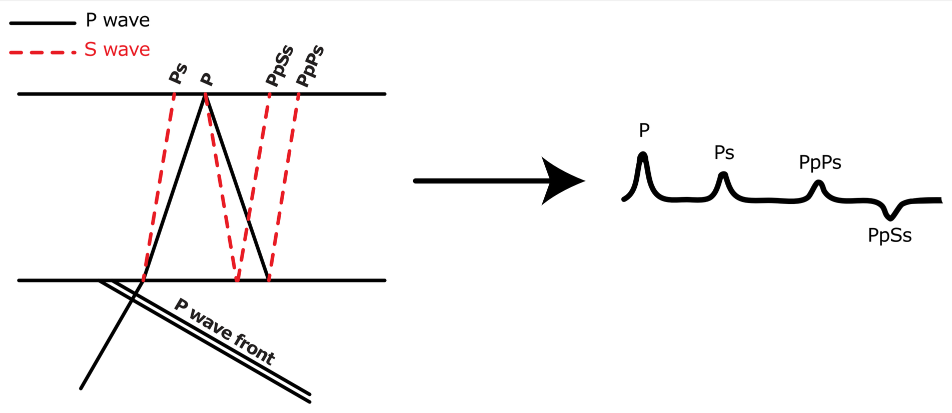


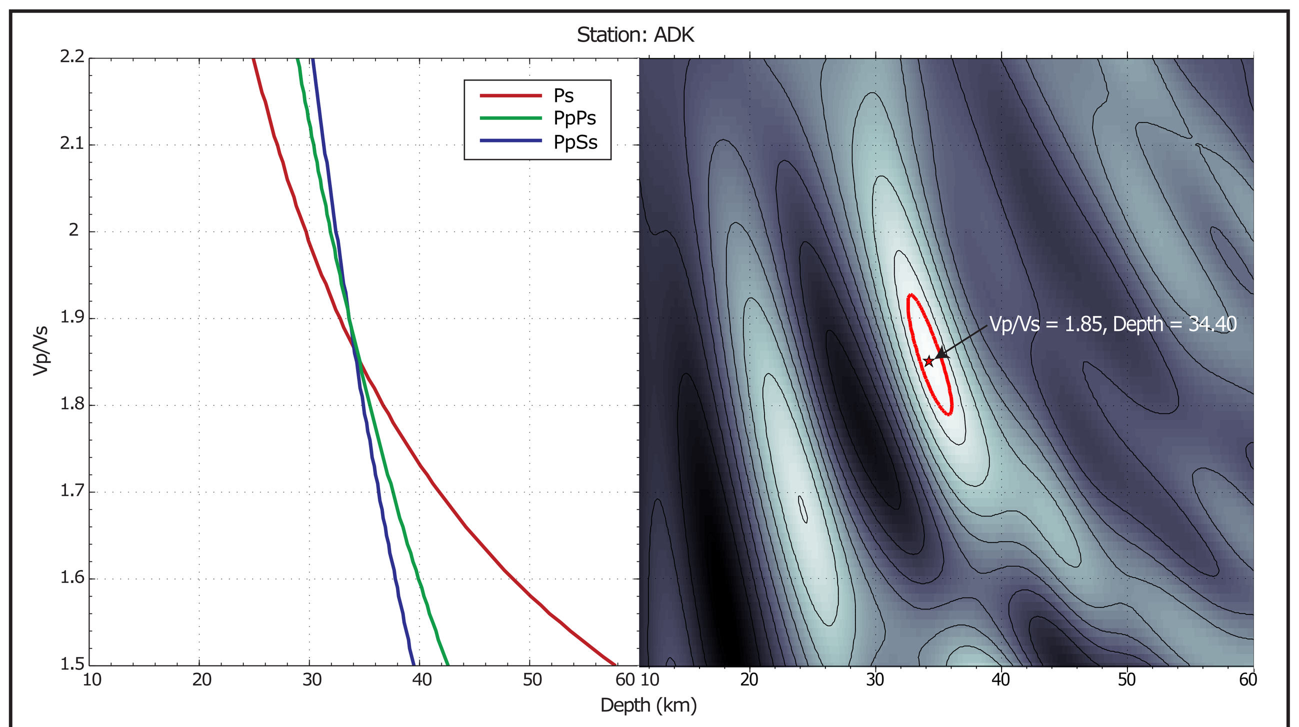
Illustration of the convolution (Stein and Wysession, 2003).

At abrupt boundaries seismic waves reflect, refract, and convert from P to S waves. Receiver functions record these interactions (Zhu and Kanamori, 2000; Rossi, et. al., 2006). We used the radial component of the receiver function. It indicates three reflections: Ps, PpPs, and PpSs.



A cartoon illustrating how a receiver function records three reflections off the same boundary.

P waves travel faster than S waves; therefore, the three reflections will arrive at different times, but will be indicative of the same boundary at the same depth. The difference in time between the initial P wave arrival and a reflection's arrival is dependent on the depth of the boundary, the ratio of the P to S wave velocities, and the ray parameter. In the Aleutian crust $V_p = 6.5$ km/s. This leaves the depth and V_s unknown. The three equations will be individually satisfied by various combinations of depth and V_s values. Taken together they determine the pair of values that best satisfies all three equations. Forward modeling was used to generate synthetic receiver functions based on the results from the method described above. These were compared to the actual receiver functions, and served to check our data.



Data from ADK illustrating how the three reflections together correlate to give a ratio and depth estimate.

Results and Interpretations

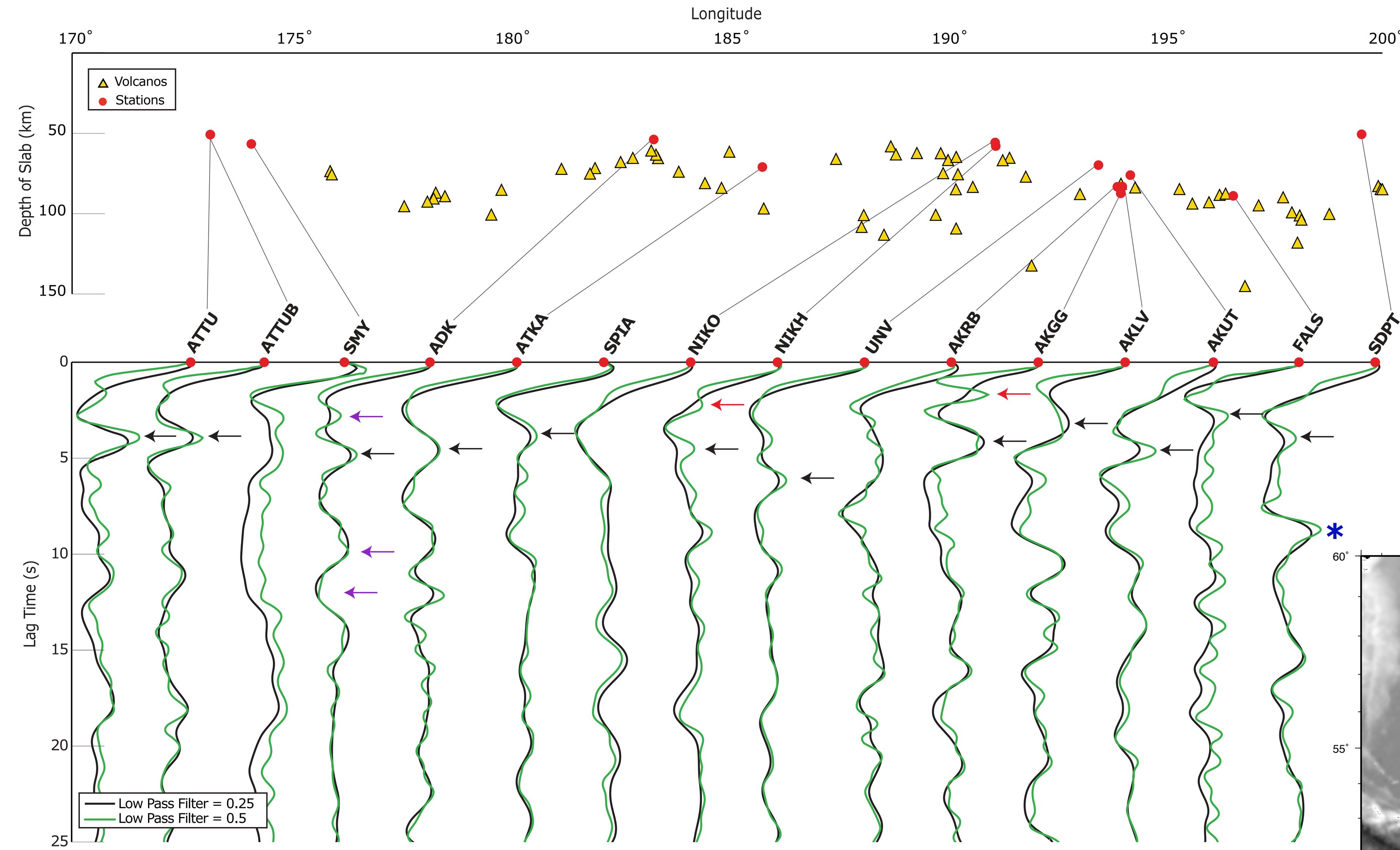
I. All Stations

A total of 378 receiver functions were used for analysis. Each station used between 8 and 45 receiver functions. Back azimuths from 170°-280° and 70°-110° were generally well represented in the data. There is very little data from 110°-170° for all stations.

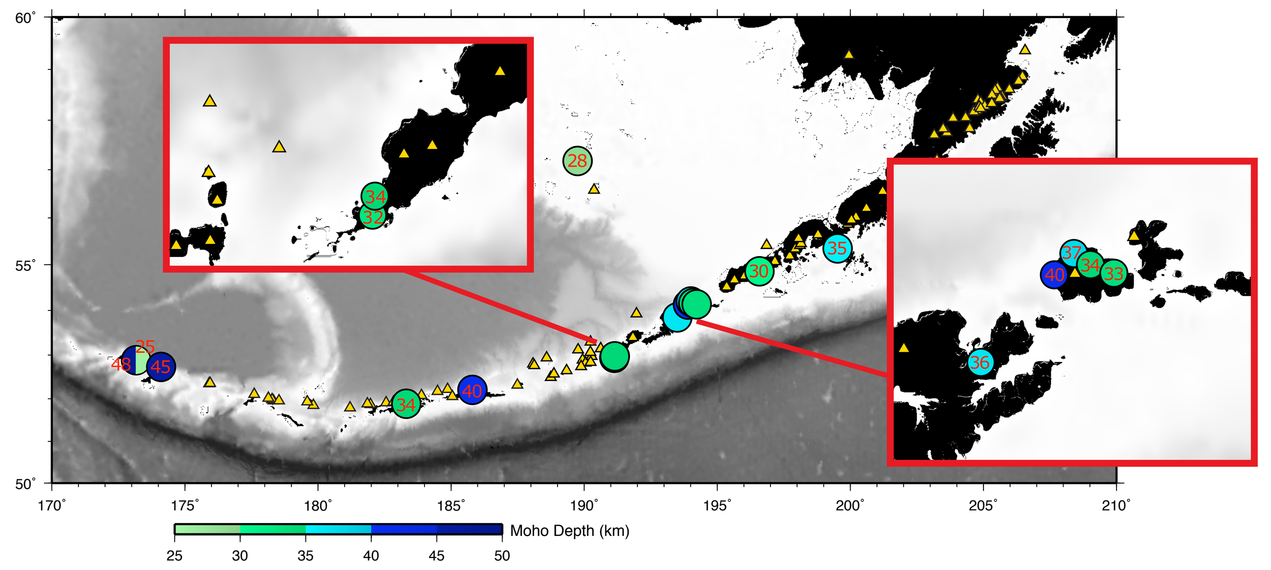
Many of the receiver functions showed strong Ps multiples around 5 s, indicating a boundary around 35 km. This was interpreted as the Moho. The map below shows the depths of the Moho underneath all the stations. The PpPs and PpSs multiples were typically not obvious. This prevented us from getting reliable estimates of V_p/V_s, and in some cases made the depth of the interface equally unclear. This problem likely arose due to the complex geometries associated with island arcs - in particular the dipping slab. This method of receiver function analysis does not account for dipping layers. A shallow or steeply dipping slab could drastically alter the travel times of the later multiples relative to the Ps multiple.

Ps multiples around 2.5 s were seen at ADK and NIKH, which indicated a boundary around 24 km. These are interpreted as a lower crustal discontinuity.

Many of the stations' receiver functions exhibited a large dependence on back azimuth. In particular AKRB, AKGG, and AKUT showed high variation in the first 5 s of the receiver function dependent on back azimuth.



The figure above shows two sets of filtered receiver functions for each station. The black arrows indicate the Ps multiple for the Moho. The red arrows indicate the Ps multiple for a shallower interface. The purple arrows indicate the Ps, PpPs, and the PpSs multiples for a shallower layer under ADK. The blue star indicates the Ps multiple off the subducting slab under SDPT.

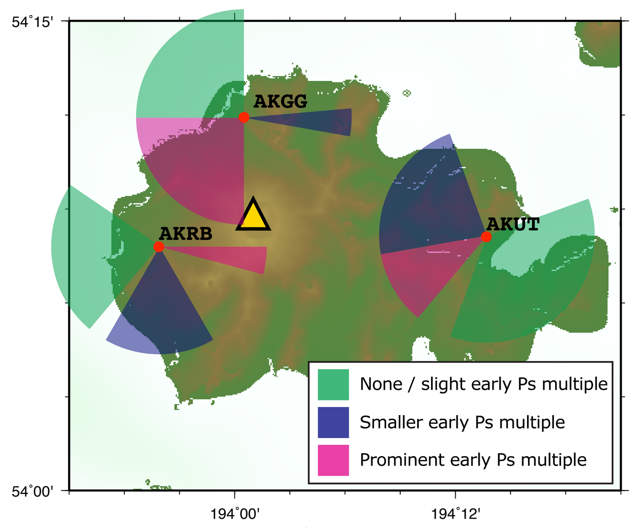


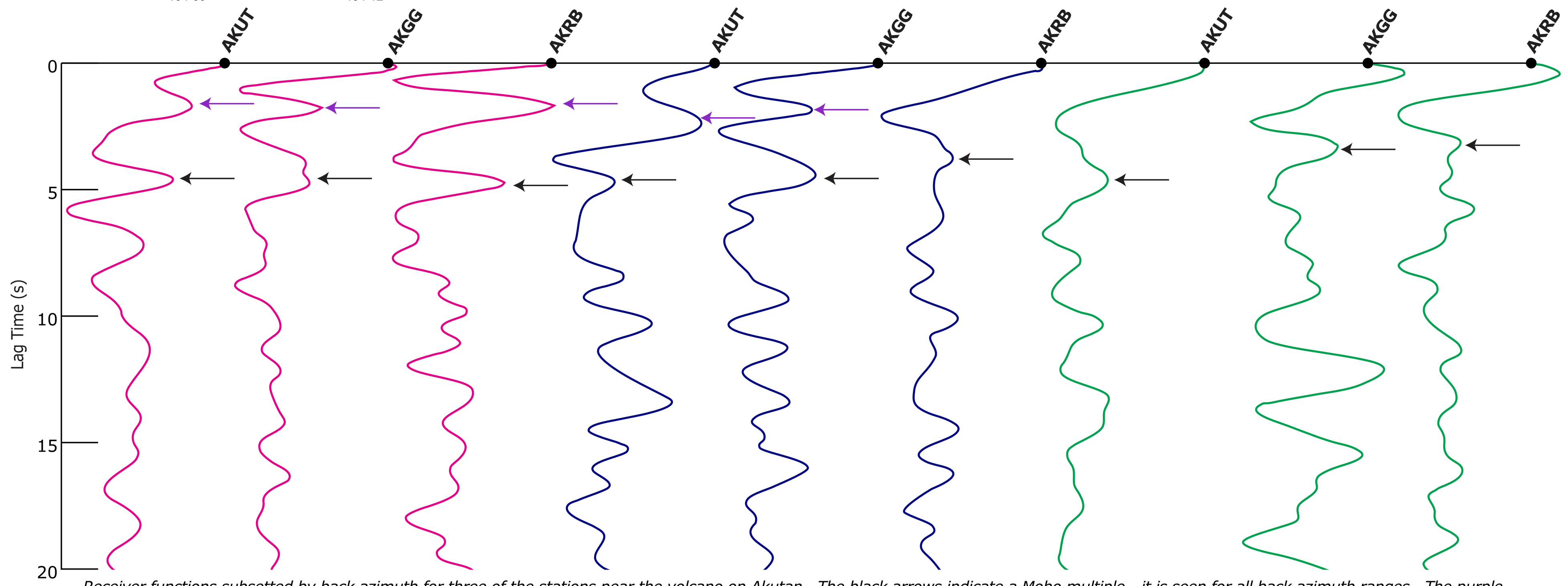
II. Akutan

Three of the four stations on the island of Akutan (AKRB, AKGG, and AKUT) showed large variation with back azimuth in shallow layers. This variation is dependent on the station's orientation towards the volcano on the middle of island as shown in the figure to the left. A large Ps multiple appears around 1-2 s for back azimuths towards the volcano, but is absent for other directions (as illustrated in the figure below).

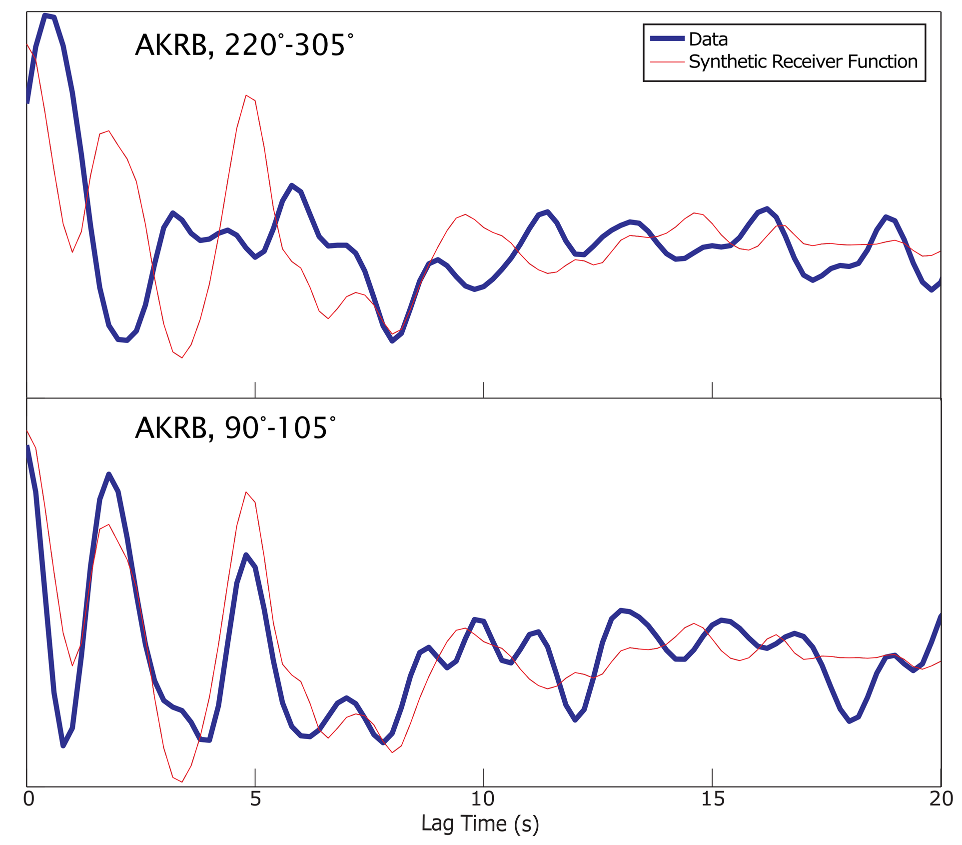
The stacked receiver function data for these stations indicate a boundary around 10-13 km with a V_p/V_s range from 1.8-1.95. Due to the shallow boundary, high ratio, and the dependence on orientation with respect to the volcano, these receiver functions are likely showing evidence of a magma chamber. The receiver function stacking method has limited ability to show shallow layers (<10 km). For this reason, we used forward modeling extensively with these three stations.

AKLV is not included in this set simply because of limited data - it had only 8 receiver functions. During the time period for which we have earthquake data, AKLV was turned on only for part of 2008.





Receiver functions subsetted by back azimuth for three of the stations near the volcano on Akutan. The black arrows indicate a Moho multiple - it is seen for all back azimuth ranges. The purple arrows indicate strong shallower multiples indicative of a magma chamber. They are only seen for earthquakes that traveled under the volcano. The colors of the receiver functions are correlated with the sectioned back azimuths in the map above.



III. Akutan Modeling

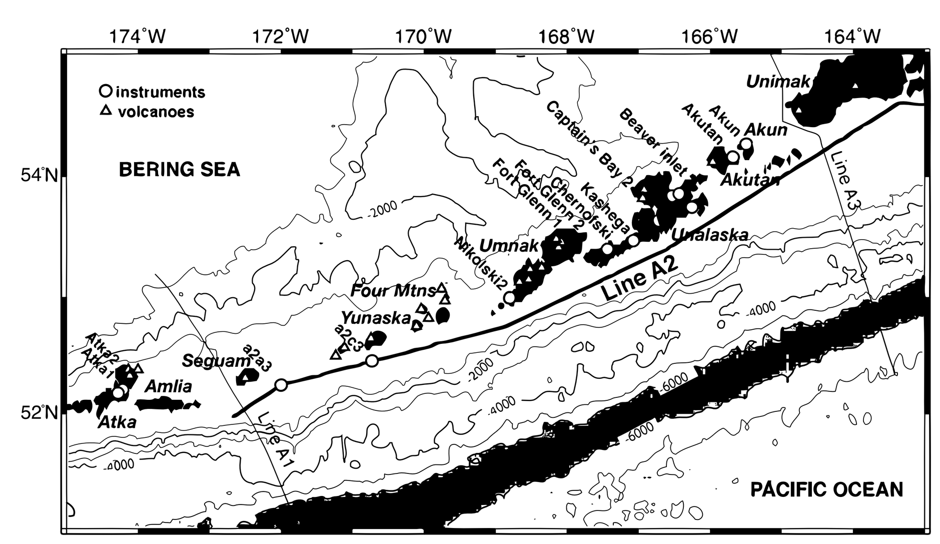
Above are two forward models generated for AKRB with the specified back azimuths. They both use a model that includes a magma chamber - it only fits for the 90°-105° range. Such models were generated for AKRB, AKGG, and AKUT focusing on the shallow structure. Models with a shallow, thin low velocity layer best fit the early receiver function. The depths and ratio values for this layer at each station are as follows:

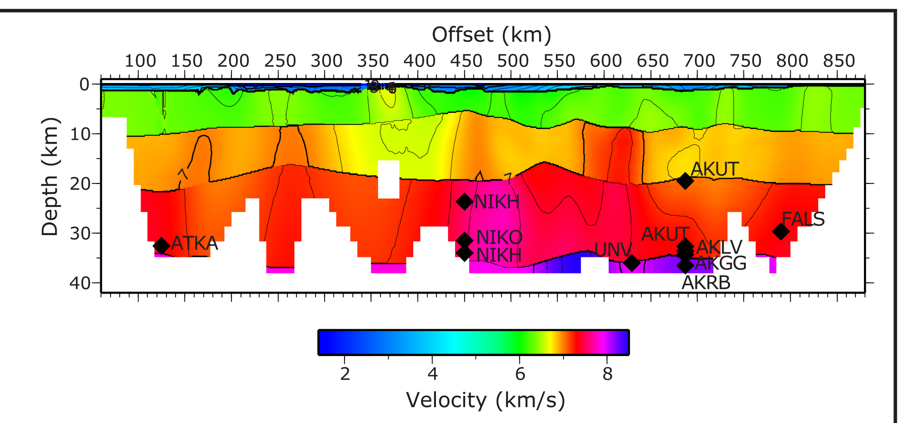
- **AKRB:** 6.3- 9.0 km deep, $V_p/V_s = 2$
- **AKGG:** 6.9- 10.0 km deep, $V_p/V_s = 1.99$
- **AKUT:** 6.1- 7.8 km deep, $V_p/V_s = 2.03$

These values were based on synthetic receiver functions generated for the back azimuths indicated in pink in the map. This layer is interpreted as the magma chamber.

Conclusions

1. We compared our data on the depths on the interfaces to the results from Shillington et. al., 2004 for stations that were common to both, or for stations that were in the same general area. Overall the data is in agreement, which validates our methodology as well as supports the findings of previous active source seismic studies.
2. We are not able to give conclusions about the composition of the lower crust in the Aleutians. Our V_p/V_s data were not well restrained due to the problems with the later multiples in the receiver functions. This was made very apparent in forward modeling - later multiples of the synthetic receiver functions far exceeded the multiples in the data they were trying to match. A more sophisticated receiver function methodology will be needed to cope with the complex geometries seen in the Aleutians.





Left: Map from Shillington et al., 2004 illustrating the line along which the active source seismic data was collected (Line A2) and the stations that were used.
Above: The velocity profile along that line, with boundary depths from this study plotted over it.

Acknowledgements

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Citations

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