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An Assessment of the Performance of the *Earthscope Automated Receiver Survey*: A User's Guide to *EARS*.

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An Assessment of the Performance of the
EarthScope Automated Receiver Survey:
A User's Guide To *EARS*.

By

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ABSTRACT

An Assessment of the Performance of the *EarthScope Automatic Receiver Survey*:

A User's Guide to EARS.

With the advent of digital seismic recording, the ability to process and interpret large quantities of seismic data has become increasingly vital. EarthScope Automated Receiver Survey, EARS, was launched in 2005 to estimate bulk crustal properties in real time, at all broadband seismograph stations, globally. EARS utilizes the receiver function HK stacking method to estimate a station's crustal thickness (H) and ratio of P wave velocity (Vp) and S wave velocity (Vs), known as Vp/Vs (K). Receiver function analysis observes the arrival times and amplitudes of five phases (Ps, PpPs, PsPs, PpSs and PsSs) that are generated within the Earth; HK stacking converts amplitude into a function of thickness and Vp/Vs. EARS processes data automatically, updating a station's H and K estimates as new events are converted to receiver functions and added to the HK stack, where the thickness and Vp/Vs estimate is shown as a global maxima in the HK plot. As of July 1st, 2021, the EARS database consisted of 7,032 stations globally, and has processed over 1.4 million radial receiver functions. Since its release, detailed analysis has not been performed on the robustness of the estimates that EARS is producing. The goal of this research is to assess the reliability of the results and how they have been affected as the database has grown. Establishing strengths and limitations is essential, not only for

improving EARS but also when utilizing its results in other fields and studies across the scientific community. To assess reliability, comparisons were made to other existing crustal thickness models Crust1.0 and Crust2.0. Standard deviations of H and K estimates were calculated for all stations, with analysis being conducted on how the standard deviation is impacted by number of events and quality of events used, along with examining the metadata. EARS has been cited over 100 times, being utilized in geophysical research and crustal thickness analysis across the globe. Here, we attempt to compile recommendations on how to best implement EARS and identify various parameters to look for in automated seismic analysis to improve its utility.

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Chapter 1: Introduction

1.1. EARS

The EarthScope Automated Receiver Survey (EARS) was launched in 2005 with the aim to estimate bulk crustal properties, at all broadband seismograph stations worldwide, in real time (Crotwell, 2007). To estimate crustal properties, EARS utilizes the receiver function HK stacking method from Zhu and Kanamori (2000). Receiver function analysis is a technique that utilizes the arrival times and amplitudes of specific phases that are generated at layers within the Earth's crust. In the HK stacking method, amplitude is converted to crustal thickness (H) and the ratio of P wave velocity (Vp) and S wave velocity (Vs) in the crust, referred to as Vp/Vs (K). These arrival times are summed to find a best fit combination for H and K. In this study, the terms "thickness" and "Vp/Vs" will always refer to crustal estimates.

EARS processes data automatically, updating a station's thickness and Vp/Vs estimate, as new events are converted to receiver functions and added to the HK stack. This makes EARS different from other traditional seismic methods, which require human input and processing for each event. Due to this, EARS is able to process extremely large quantities of data using measurable standards of quality to determine which events to use within the HK stack. To estimate crustal properties, a P wave velocity is required. The Vp

can vary and is dependent on the crust type, so the Vp determined by the crustal model Crust2.0 is used for each station (Bassin et al., 2000).

The TA and US networks are two networks operating in the United States (Figure 1.1). The Transportable Array (TA) consists of portable seismic stations that run for approximately two years in select locations across the United States (EarthScope*, 2007)*. The US network is a permanent network of stations operating continuously in the United States. These two networks will be the primary focus of this study within the continental United States, as they contain both long running and temporary stations and have substantial coverage throughout the country

1.2. Characterizing the EARS Data Base

EARS is hosted by Incorporated Research Institutes of Seismology (IRIS) at http://ds.iris.edu/ds/products/ears/ and utilizes seismic data stored at the IRIS Data Management Center (DMC). Due to the automated nature of EARS, results change daily as new seismic events occur. With this consideration, July 1st, 2021 was chosen to download all the data available in the database so analysis was being performed on an unchanging dataset. As of July 1st, 2021, the EARS database consisted of 7,032 stations globally, and has processed over 1.4 million radial receiver functions (Figure 1.2). The data includes HK plots, thickness, Vp/Vs, and standard deviations for both values, using the Vp determined from Crust2.0.

A majority of the globe's crustal thickness falls between 25 and 45 km (Figure 1.2). Percent fit is a means of determining if an event is of high enough quality to be used for crustal property analysis, and will be discussed in more detail in the analysis section.

A majority of the TA network has 20 to 60 events with an 80% or above fit, with most the US network stations having 200 or more events (Figure 1.3). Because EARS has a cut off of 80% fit, this is the number of events that are used in the stack for the EARS crustal property estimates. Globally, most stations have 50 events or less used to estimate their Vp/Vs and thickness. Note, the spike at 200 events is due to EARS database having a limit of 200 events in the HK stack. However, several stations have more than that, in varying amounts, leading to a jump at exactly 200 in the dataset.

When considering the nature of EARS and the distribution of stations, it becomes clear that this is a heterogenous dataset. Standard deviation of estimates can vary greatly from station to station; ranging from less than 1 km to greater than 15 km (Figure 1.4). This increases the need to determine when and where the results are robust, since a station's features can differ greatly from one region or area to the next. Location, geology, number of events, and station runtime are all variable across the globe and that is evident within EARS results.

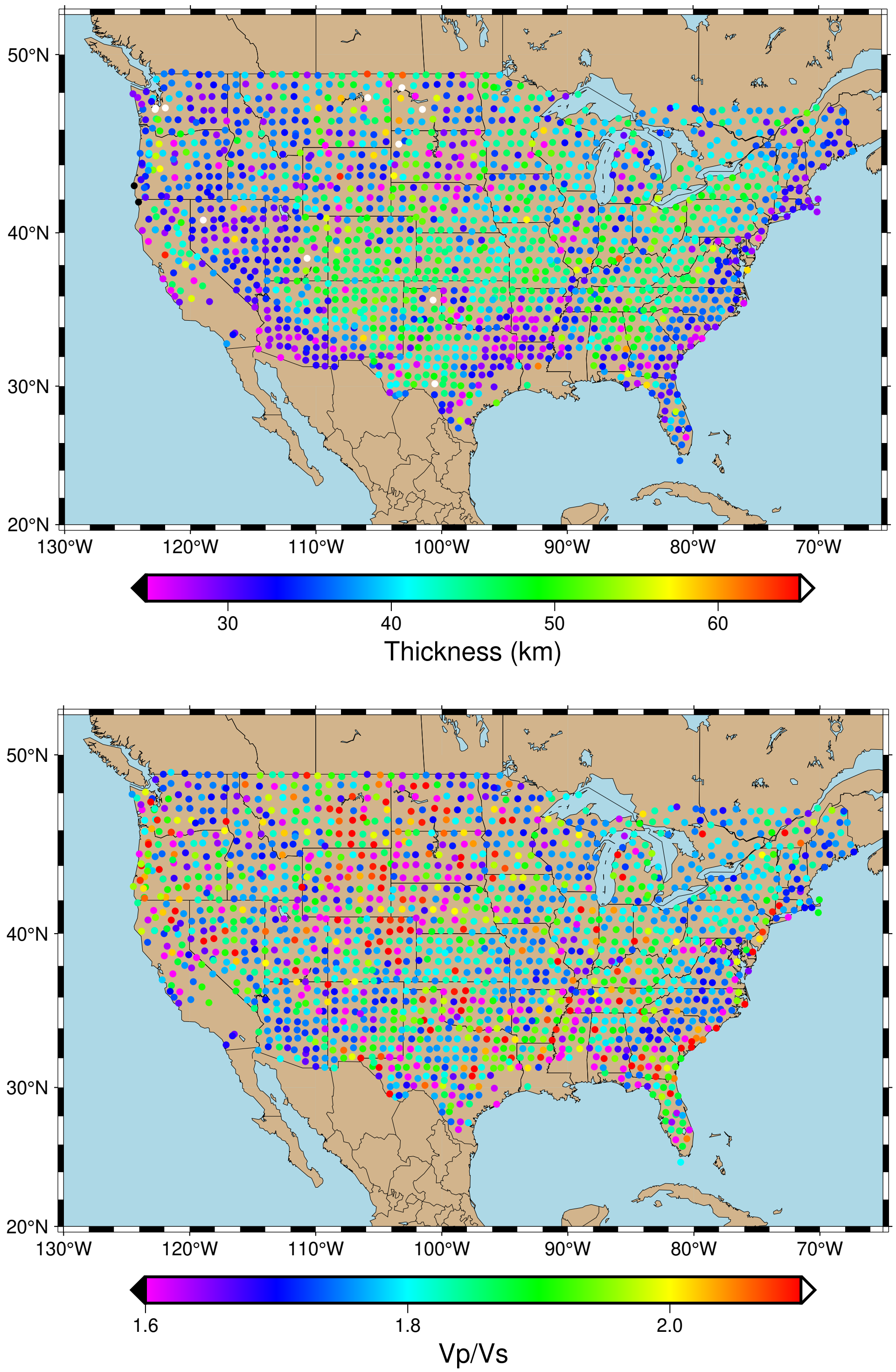


Figure 1.1: EARS maps of estimates; Thickness (top) and Vp/Vs estimates (bottom) of continental United States using stations in the US and TA networks.

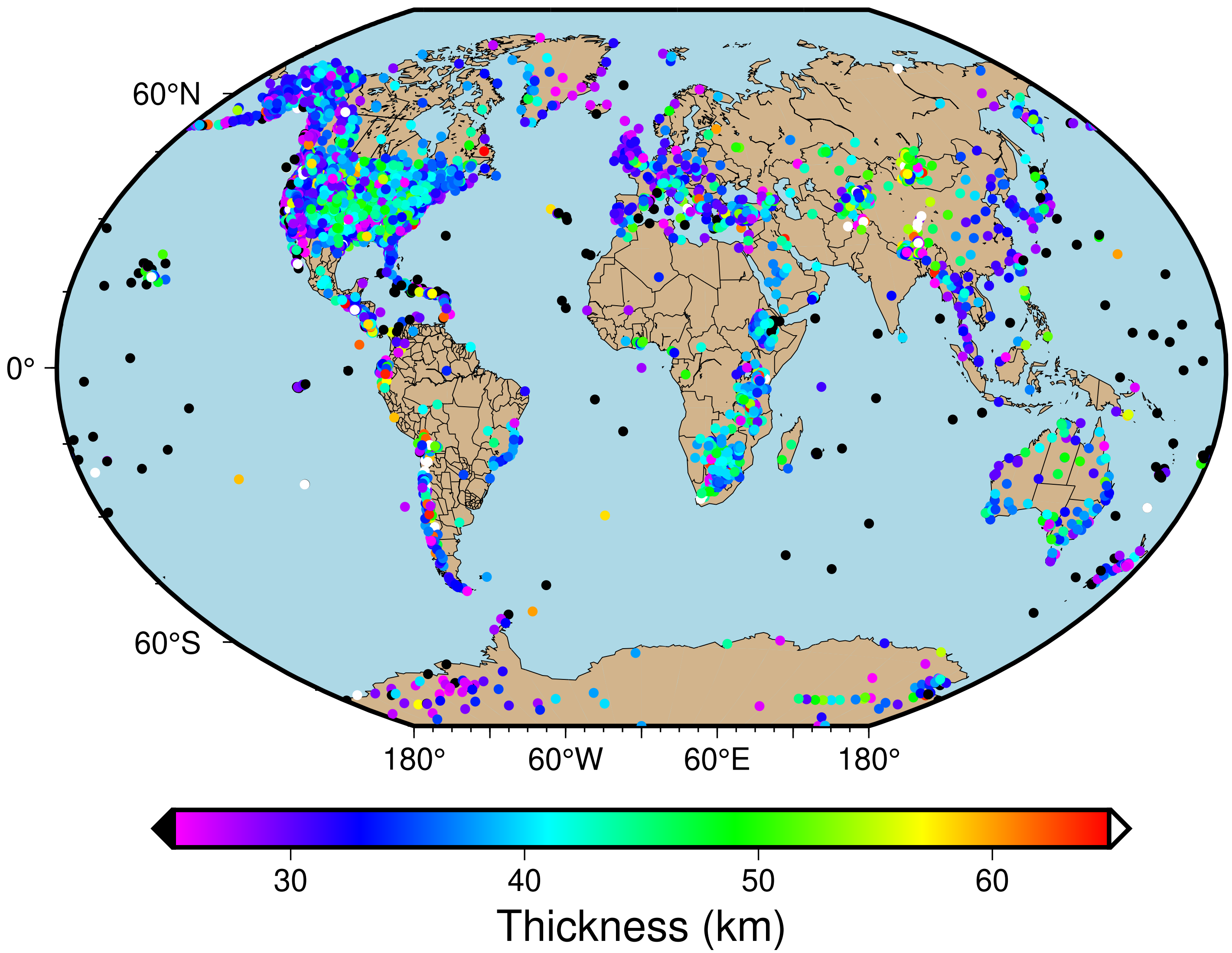
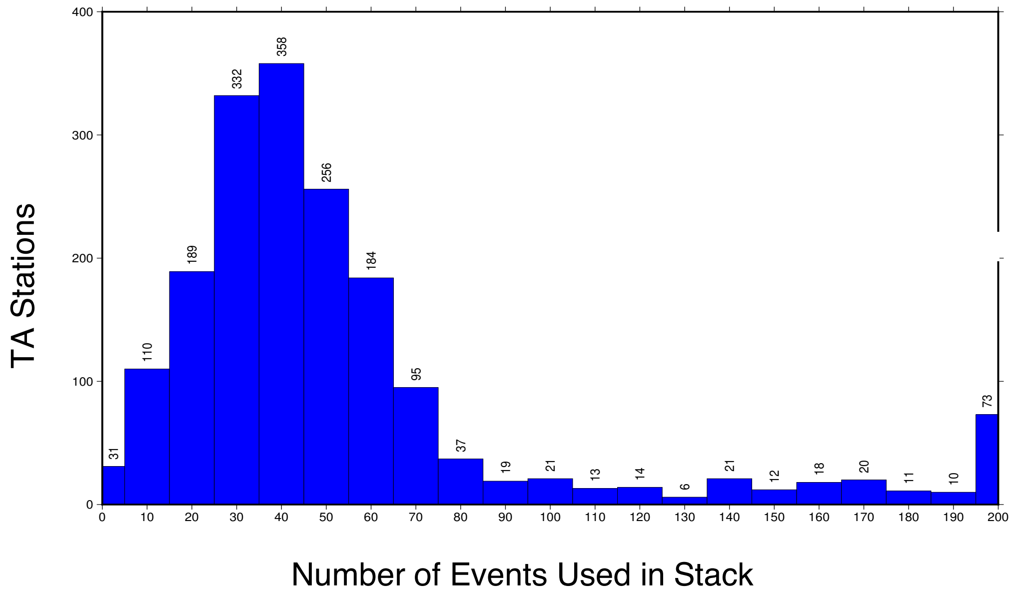


Figure 1.2: Global map of EARS crustal thickness estimates, as of July 1st, 2021



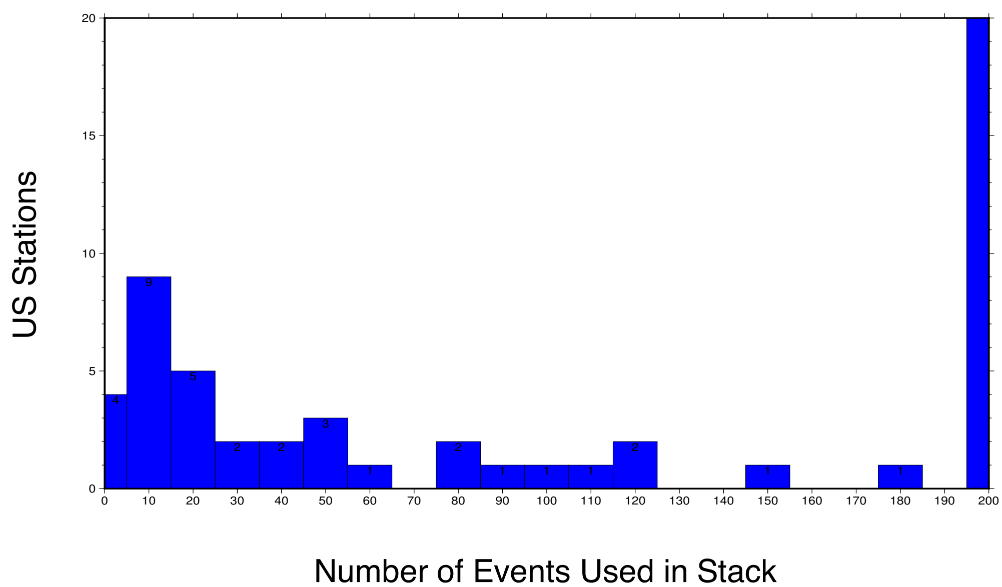


Figure 1.3: TA and US Distribution of number of events used for crustal property estimates for the stations in the TA network (top) and US networks (bottom). Both histograms include only stations within the continental United States with only events 80% fit and above being utilized. The US network has 52 stations with 200 or more events.

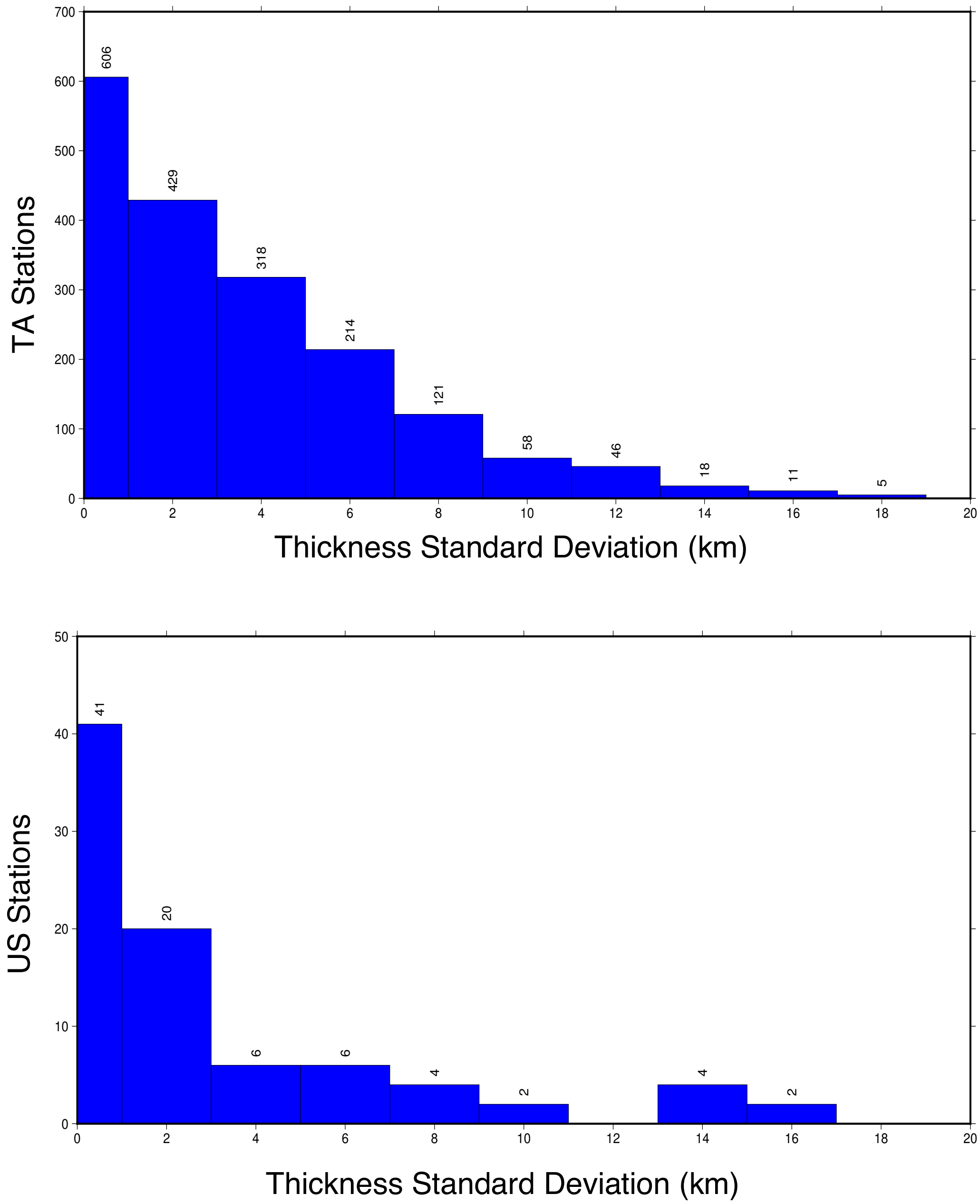


Figure 1.4: Histogram of crustal thickness standard deviations for stations in the TA network (top) and US network (bottom). Approximately 40% of TA and 48% of US stations have a standard deviation of less than 2 km.

1.3. Receiver Functions and HK Stacking

When seismic waves propagate from an event, they encounter layer boundaries, or velocity discontinuities, within the Earth's crust, which cause reverberations where P waves convert to S waves (Figure 1.5). Receiver function analysis is a technique used in seismic studies, that examines the amplitude and timing of these reverberation arrivals. There are five reverberations that occur at a layer boundary which generate significant energy to be visible in receiver functions. These five phase reverberations are Ps, PpPs, PsPs, PpSs and PsSs (Figure 1.6).

EARS receiver functions are calculated through a process called iterative deconvolution (Ligorrîa et al., 1999). This form of seismic analysis is ideal for EARS because it can be automated and can be more stable than other techniques that require human intervention to determine stability. A seismic station records three types of ground movement; radial, tangential and vertical. Radial and tangential are the horizontal response at the station, and are orthogonal to each-other. Iterative deconvolution observes the difference between the horizontal and the vertical impulse response. In this technique, when there is a large correlation or anticorrelation between the horizontal and vertical components, there also is a large spike in amplitude, or pulse in the data that can be extracted (Ammon et al., 1999). These spikes are the P to S wave reverberations listed prior. The vertical component is subtracted from the radial component, over several iterations, until the difference becomes negligible (Ligorrîa et al., 1999).

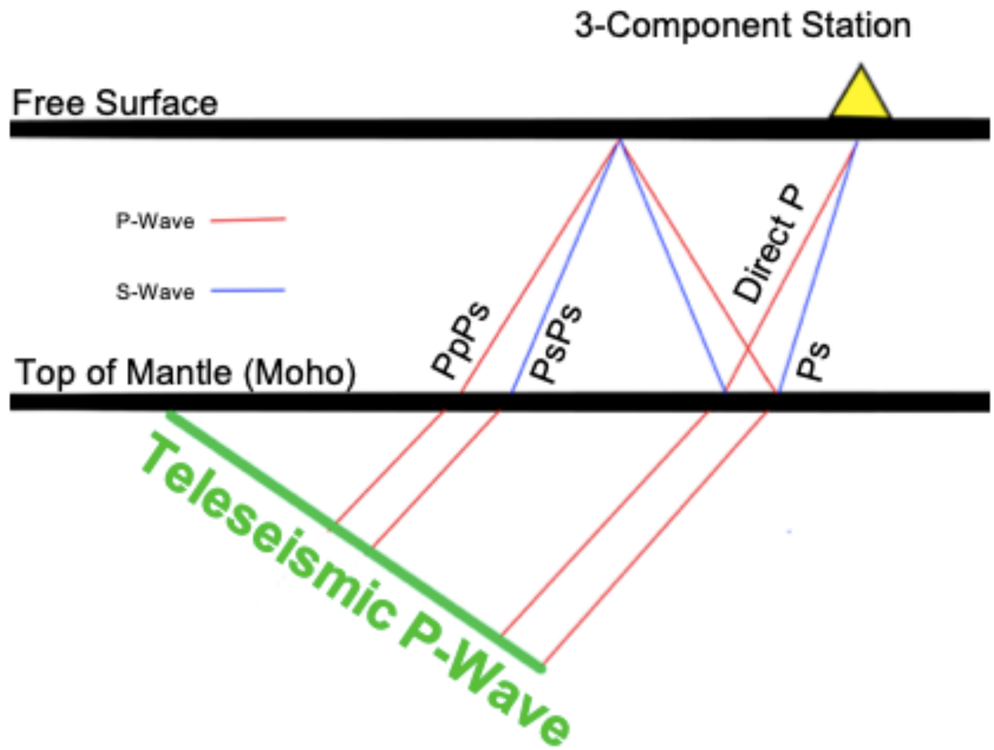


Figure 1.5: Simplified illustration of ray paths in Figure 1.6. Notation for each leg of the path begins with capital “P”, which is prior to encountering the Moho. After the mantle, lowercase signifies upward moving phases, towards the free surface, while uppercase represents downward going phases, away from the free surface.

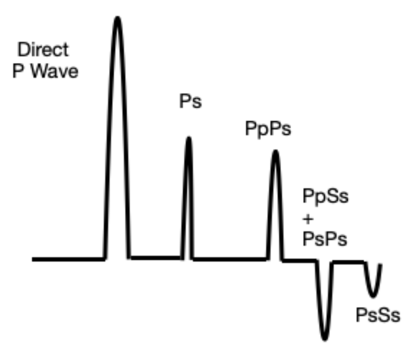


Figure 1.6: Illustration of a radial receiver function with corresponding wave phases. PpSs and PsPs arrive at the same time.

The arrival timing and the amplitude of these converted phase reverberations are stacked over several events to determine Vp/Vs and crustal thickness. Vp/Vs is used because the timing of the phase arrivals is not heavily influenced by absolute Vp or Vs values (Ammon et al., 1990). Therefore, the Vp is used from Crust 2.0 (Bassin et al., 2000) and a best fit pair of velocity ratios and thickness is calculated. This is possible due to the unique relationship that exists between the thickness of the crust, wave velocities, and the arrival of each phase (Ammon et al., 1990).

These relationships are defined by:

$$
\begin{aligned}
t_{Ps} - t_P &= H(\eta_\beta - \eta_\alpha) \\
t_{PpPs} - t_P &= H(\eta_\beta + \eta_\alpha) \\
t_{PsPs/PpSs} - t_P &= 2H\eta_\beta \\
\eta_\alpha = \sqrt{\frac{1}{V_P^2} - p^2} &\text{ and } \eta_\beta = \sqrt{\frac{1}{V_S^2} - p^2}
\end{aligned}
\tag{1.1}
$$

Where the phase arrivals are notated by the subscripts for each t, and p is the ray parameter.

An alternative to HK stacking is simply summing the receiver functions. This method is not effective for EARS since summing the receiver functions depends on the ray parameter, which depends on distance. As the distance from the source increases, the arrival times for each phase changes, limiting the ability to stack events from several distances. The HK stacking method is utilized to remove the dependence on the ray parameter, so that events from any distance can be used. In HK space, amplitude becomes a function of thickness (H) and Vp/Vs (K) (Zhu and Kanamori, 2000).

Stacking multiple events allows a better signal to noise ratio, dampening incoherent signal and amplifying the phase arrival signals (Figure 1.7). Once multiple receiver functions are stacked, the thickness estimate is shown as a global maxima in the HK plot (Figure 1.8). Additionally, other local maxima exist within the HK plot that can indicate other strong arrivals existing in the stack (Figure 1.9). Converting the receiver functions from the time domain to the HK domain requires summing the amplitudes of predicted arrival times for all combinations of Vp/Vs and H, calculated using Equation 1.1 (*Crotwell, 2007)*. Once all arrival times are calculated, the HK stack is given by the formula:

$$s(H,k) = \sum_{k=1}^{N} \left(w_1 r_k(t_{Ps}) + w_2 r_k\left(t_{PpPs}\right) - w_3 r_k(t_{PsPs}) \right) \quad (1.2)$$

In this formula, r_k(t) is the kth radial receiver function in the HK stack. Each phase arrival time is given by t with the respective phase in the subscript. Note that the reversed polarity of the PsPs phase is indicated by the negative sign. Each w represents the weight given to each phase arrival, in the stack. EARS sets the weights of all phases to 1/3. The PsSs is not included in the stack as its energy is not significant enough to have an impact on the results. In HK space, the relationship between Vp/Vs and thickness is apparent by the pattern that is present in the "shape" that exists in all global and local maximas. A noticeable trend in HK plots is upper right, towards lower left. This occurs due to the stacking of the phase arrival times and their specific trade-off between Vp/Vs and thickness, where thinner crusts cause larger Vp/Vs ratios and thicker crusts allow for larger Vs values, causing smaller Vp/Vs ratios

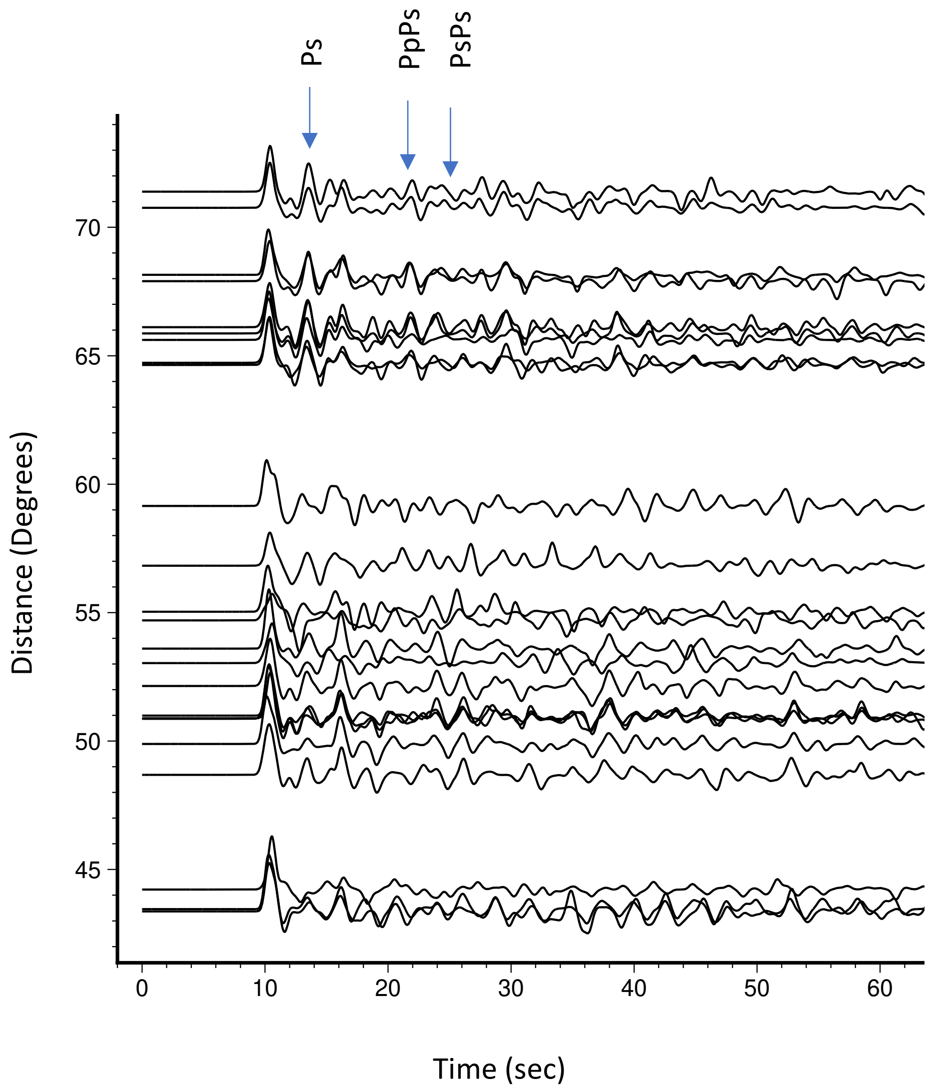


Figure 1.7: TA.R22A radial receiver function record section. Approximate Ps, PpPs, and PsPs/PpSs arrivals marked with arrows occurring at approximately 13.5 seconds, 21.5 seconds, and 24.9 seconds respectively for a 71 degree ray parameter, using Formula 1.1. Values for crustal thickness, Vp and Vp/Vs from HK stack: thickness of 44.24, Crust2.0's Vp of 6.306 km/s, Vp/Vs of 1.855

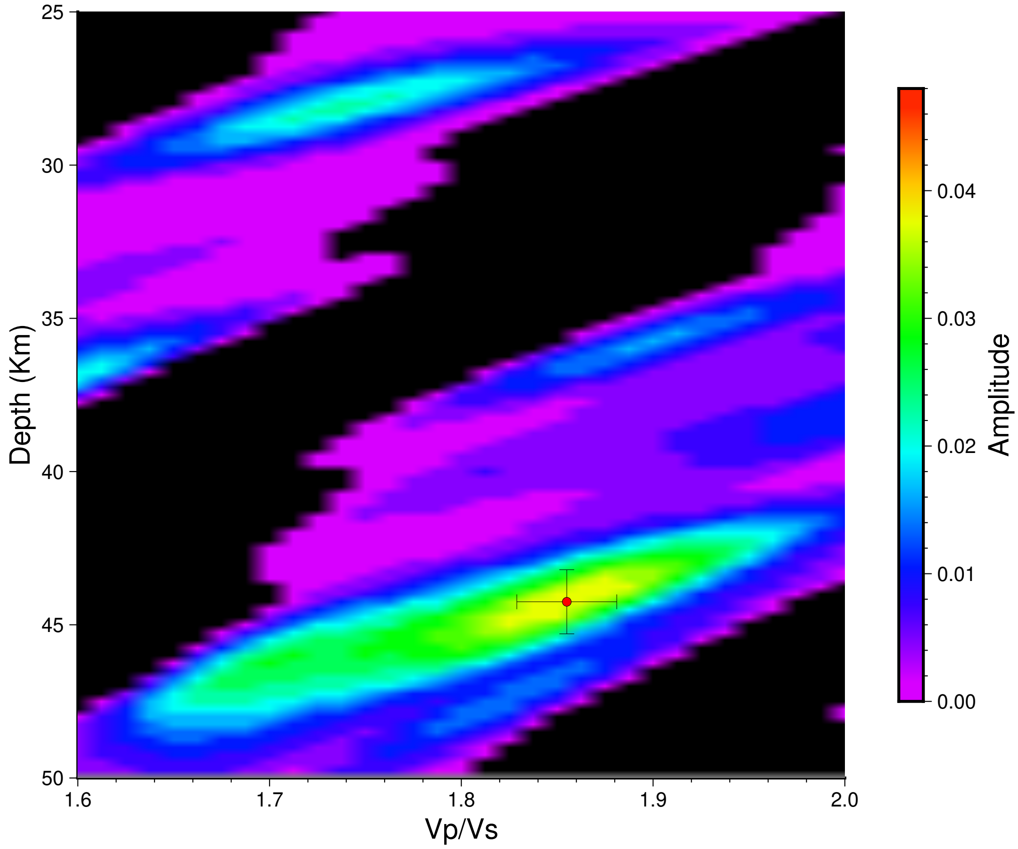


Figure 1.8: HK plot showing amplitude as a function of Vp/Vs and thickness. Station shown is TA.R22A. The global maxima of the plot is marked by a red circle with error bars for thickness and Vp/Vs. The thickness estimate of this station is 44.24 km with a standard deviation of 1.045 km. The Vp/Vs is 1.855 with a standard deviation of 0.026.

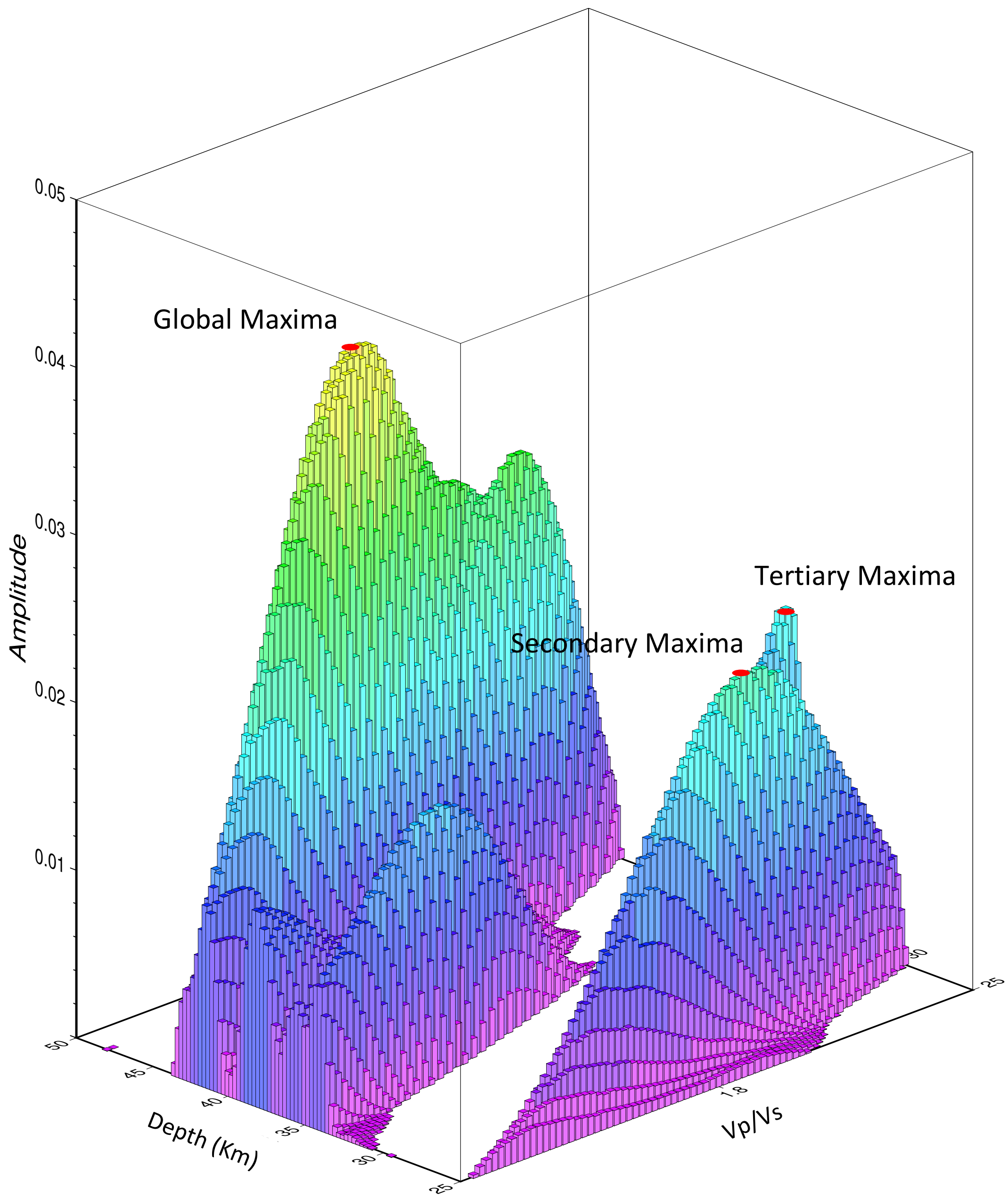


Figure 1.9: Perspective HK plot showing amplitude as a function of Vp/Vs and thickness. Station shown is TA.R22A. The maxima of the plot are marked by a red circle. The global maxima shows the thickness estimate of this station as 44.24 Km and Vp/Vs of 1.855 with the secondary maxima being 28 km and 1.745 Vp/Vs and tertiary maxima having a result 36.75 km and a Vp/Vs of 1.605.

1.4. Poisson's Ratio and Vp/Vs

In addition to Vp/Vs ratios, an important value is Poisson's ratio (σ). Poisson's ratio is a ratio of the latitudinal and longitudinal strains and measures the amount a material expands when squeezed, or contracts when stretched. It is related to Vp/Vs by:

$$\sigma = \frac{(Vp/Vs)^2-2}{2(Vp/Vs)^2-2} \quad (1.3)$$

Poisson's ratio is sensitive to composition, with higher values indicating a higher mafic content and lower values indicating a higher silica content (Zandt et al., 1995). Common rocks have σ values between 0.20 and 0.35. EARS HK stacks have a Vp/Vs range of 1.6 to 2.1, which equates to a σ range of 0.179 to 0.353. This is useful in determining if other maxima are more geologically realistic when reviewing EARS stations that have extreme Vp/Vs values or are located in areas where the Poisson's ratio is well documented.

Chapter 2: Methodology

To determine the robustness of EARS' data, several forms of statistical analysis were conducted, along with comparison to other compiled crustal thickness and Vp/Vs estimates around the globe. To assess the reliability of the results EARS produces, standard deviations were calculated within each station's data set to determine large differences in possible thickness and Vp/Vs estimates. This standard deviation is calculated by a method called bootstrapping (Crotwell, 2007).

In this method, the pool of receiver functions is resampled with replacement, to create a new set of the same size, then a new global maxima is calculated. This is repeated 100 times to give a set of HK pairs from which a standard deviation can be calculated. A large standard deviation implies a large amount of variance within the data pool and suggests that the given crustal thickness estimate may not be reliable. Along with standard deviation, a value called *residual complexity* is calculated. This is a representation of how much energy exists in the HK space, once the global maxima is removed. Many HK plots have other local maxima, which are smaller than the global maxima that could represent other possible crustal thickness estimates (Figure 1.9). Once the global maxima peak is removed, if a majority of the energy was within that peak, the residual complexity will be smaller. A large residual complexity could be another indication that the global maxima may need further evaluation, since other maximas contained large amplitudes.

As a reference to other crustal thickness estimations, comparisons to data sets *Crust2.0* and *Crust1.0* have been conducted, (Bassin et al., 2000, Laske et al.,2013*)*. This was accomplished by comparing thickness differences between the two models while examining the impact of utilizing their different Vp values in calculating the HK stacks.

Stations with extreme values were determined to be any station with a crustal thickness estimate that is more than 15 km different than its neighbors, along with any station that has an estimate greater than 55 km. This was done by systematically comparing a station's thickness to all of the surrounding thickness estimates, within a 2x2 degree box. For a station to be extreme, it needed to be more than 15 km different from the average thickness estimate of its neighbors. 55 km was chosen as it is the largest thickness calculated by Crust1.0, for the continental United States. However, if several stations in an area contain extreme values when compared to their neighbors, it is important to consider the possibility of lateral discontinuities or anomalies in the crust.

Analysis was conducted on ways to have these stations better match their neighbors or to give them a more reasonable crustal thickness estimate. The solution space was limited to reflect Vp/Vs values in Crust 1.0 of 1.7 to 1.8 m/s; the current Vp/Vs boundaries on EARS results are 1.6 to 2.0 m/s. Additionally, the percent fit cut off was decreased to allow a greater number of events being utilized in the HK stack, in an attempt to amplify the signal from the crust mantle boundary.

The tangential receiver functions of these stations were observed and converted into HK stacks. This was done to determine how much energy existed in HK space for tangential components when compared to radial components, in stations that had extreme

values. Lastly, the expected primary arrival time of the zero lag for the radial and tangential components were compared to the observed arrival in the data. The average offset was calculated for each station, then compared between stations with reasonable results to those with extreme thickness estimates.

Throughout this study, specific stations will be mentioned when referencing certain concepts. These stations are PFO, in the II network, and stations M11A, 324A and R22A in the TA network. These are focused on due to not only providing robust examples of different techniques, but also cover different physiographic provinces and geological lithologies.

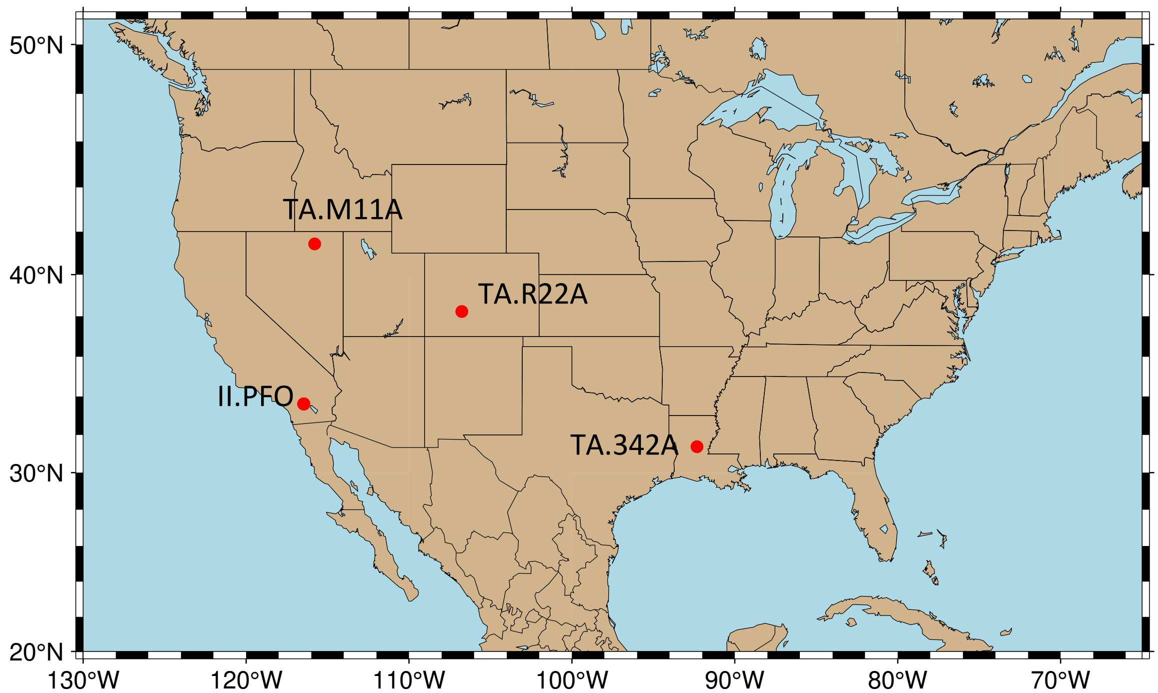


Figure 2.1: U.S. Map locations of specific stations discussed throughout this study.

Chapter 3: Analysis

3.1. Standard Deviation and Residual Power

One important measure of the reliability of a data set can be its standard deviation. For EARS, a large standard deviation occurs when the Vp/Vs and thickness pair estimated for a station varies substantially for over several events. The standard deviation for both Vp/Vs and thickness in km, is calculated during the bootstrap iteration process of the HK method. It is important to note that a standard deviation is not the deviation from any "truth" but rather the deviation within a station's individual dataset.

Along with standard deviation, residual power can be an indicator if a station's estimate is robust. Residual power is a measure of how much energy resides in a station's global maxima. If a large amount of energy exists at other H and K pairs, typically in the form of other local maxima, the residual power will be high. Due to this, analyses were conducted to determine what factors could impact standard deviation of the thickness and Vp/Vs estimates. These factors included expanding number of events, limiting the solution space, and adjusting percent fit limits.

Typically, in HK stacks larger quantities of events are preferred to amplify the desired signal. With that concept, long running stations, or stations with an abundance of good events, should reasonably have lower thickness and Vp/Vs standard deviations. An example of this can be seen in comparing the US network and the TA networks within

the United States. The US network has permanent running stations with more events utilized within the HK stack. 71 percent of US network estimates have a smaller than 3km standard deviation, with 48% having a smaller than 2 km standard deviation. Conversely, the temporary TA networks have 55% of estimates with standard deviation of 3 km or less and only 40% of standard deviations falling below 2 km (Figure 1.4).

However, in plotting number of events against standard deviation, a similar trend could not be seen throughout the entire dataset. This indicates that, while number of events and standard deviation are worth considering, additional measures are needed when determining the quality of a station's estimate. A relationship can generally be observed when comparing residual complexity to standard deviation, with higher standard deviation stations having larger residual complexities (Figure 3.1). This supports the notion that a larger standard deviation has multiple larger maxima and therefore a greater amount of energy exists outside of the global maxima.

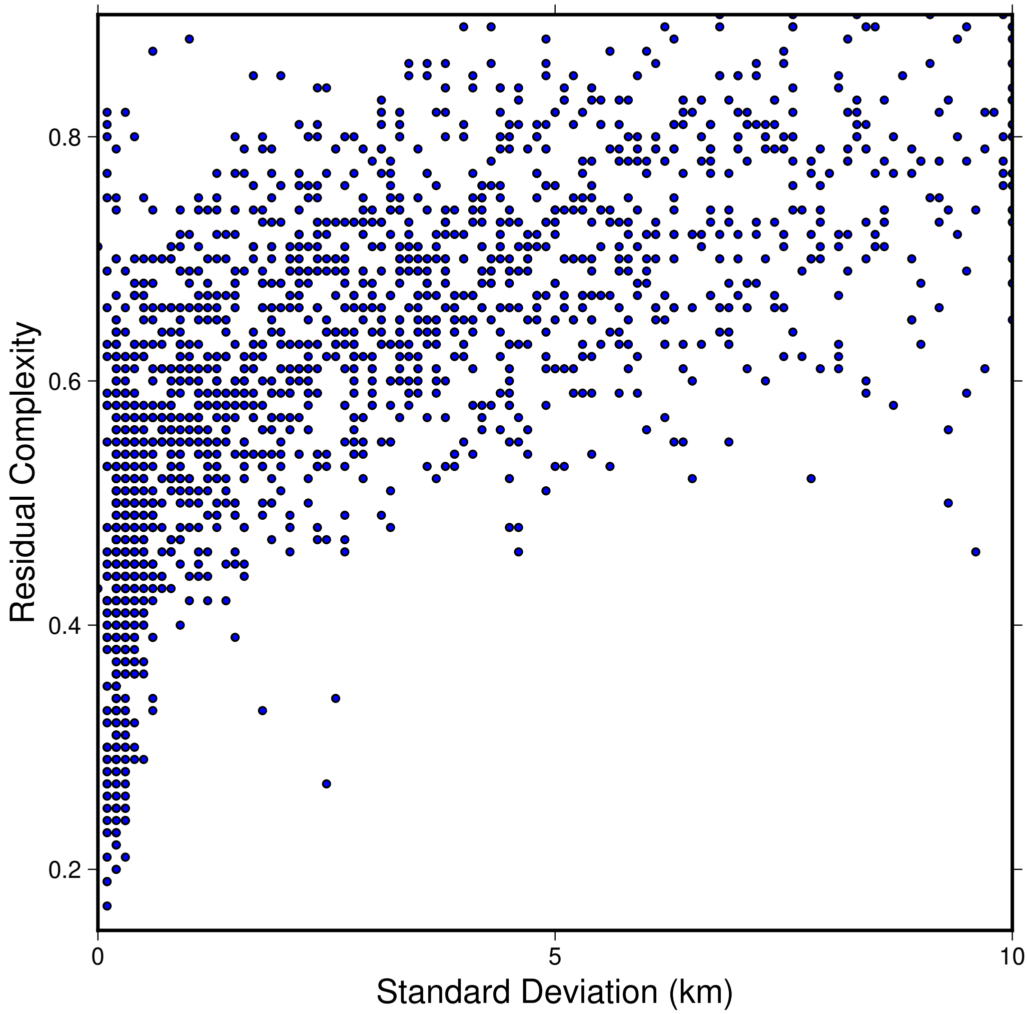


Figure 3.1 Plot of relationship between standard deviation and residual complexity

3.2. Percent Fit

A low percent fit indicates a large amount of energy remaining after the iterative deconvolution and a lower quality of data. Geology, “noisy” data or faulty equipment can impact an event’s quality. EARS data on the IRIS server has a cutoff of 80% fit and above for any events that can be applied in a stack. To determine if events with lower percent fits could be good candidates for stations that lack adequate events 80% and above, a comparison was done on the long running station PFO in the II network. This station has a low standard deviation and robust crustal thickness estimate when utilizing only events 80% fit and above. This made it an ideal candidate in determining the impact of using “less than perfect” events in the stack.

When using events with a percent fit 50-59% vs events 80% and above, the standard deviation was impacted however, the residual complexity was only very slightly affected. This is due to the majority of the energy residing in the global maxima, regardless of the percent fit of events used. In short, the peak of the global maxima became broader, with a higher standard deviation, however all results were between 29 to 31 km (Figure 3.2, 3.3). This implies that there could be a possibility that lower than 80% fit events are a viable option at stations where higher percent fit events are lacking.

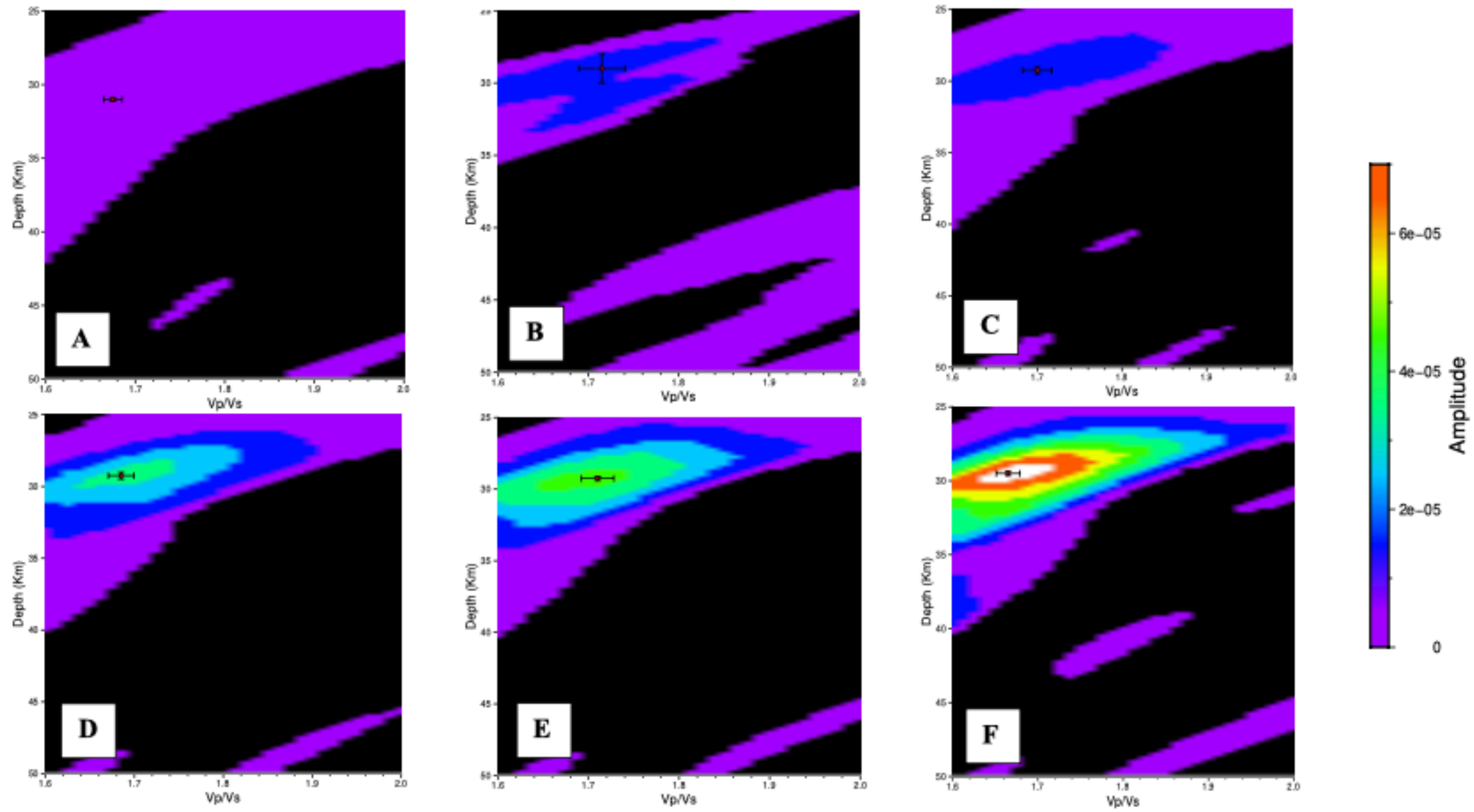


Figure 3.2: Percent fit HK plots for station II.PFO, with thickness and Vp/Vs error bars. All plot amplitudes are normalized by number of events. Panel A is all events 50 to 99.99% fit (1262 events). Panels B through F are 50%-59%, 60%-69%, 70%-79%, 80-89%, and 90-99% respectively.

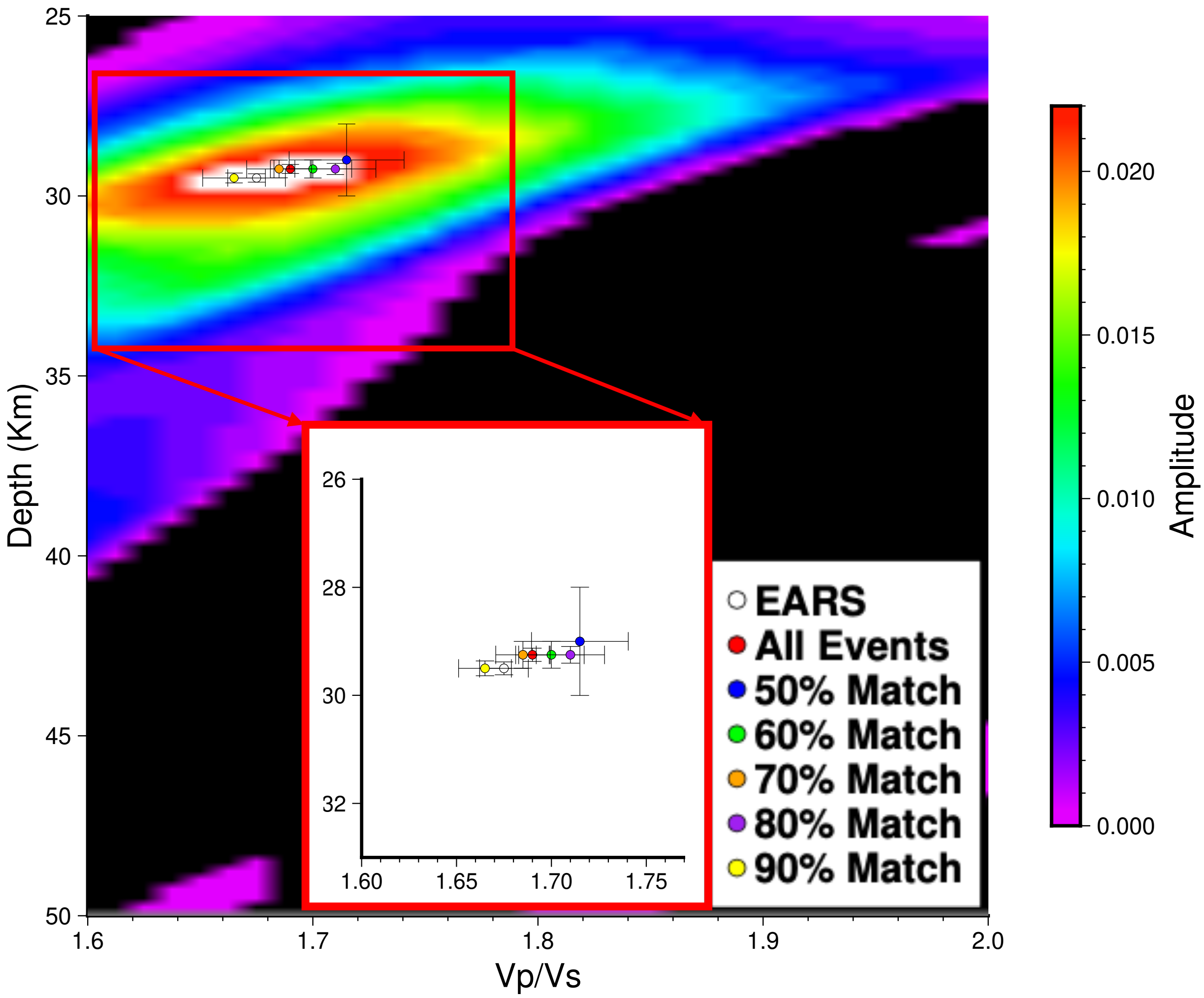


Figure 3.3: HK Plot for station II.PFO showing relative error bars from panels A-F in Figure 3.2, along with EARS' results. All Events refers to panel A, with B through F referring to 50% through 90% respectively. EARS results give a crustal thickness of 29.5 km, with a standard deviation of 0.12 km, and a Vp/Vs of 1.675 and a Vp/Vs standard deviation of 0.013.

3.3. Crust1.0 vs Crust2.0

When EARS was implemented in 2005, an available global crustal model was Crust2.0 (Bassin et al., 2000). Crust2.0 divides the globe in to 2x2 degree grid squares and determines a crustal structure for each square based on layer parameters. These parameters include layer thicknesses and various compositions, such as ice, sediments and bedrock. This allows an average Vp to be assigned to each 2x2 square across the globe, along with a thickness. For any station, EARS uses the Vp estimate assigned by Crust2.0 for the coordinate the station falls within. Released in 2015, Crust1.0 divides the globe into 1x1 degree squares and assigns Vp based off an eight-layer crustal profile that takes into consideration different tectonic settings (Laske et al., 2013). A natural response to this is to see if an improvement can be made to EARS estimates, utilizing this new global crustal model. The first step is to examine the difference in thickness estimates provided by Crust1.0 and Crust2.0 (Figure 3.4). There is a linear relationship between the two estimates, but there are some interesting aspects. Crust2.0 has a cutoff at 10 km, whereas Crust1.0 appears to go down to approximately 8 km. The stations that have large differing values between the two models could correlate with places that have two maxima which are close in amplitude, but have a large difference in thickness and/or Vp/Vs estimates. These may be stations that warrant more thorough examination into their crustal structure. During analysis, using the differing Vp estimates in Crust1.0 vs Crust2.0 had little tangible affect. In station PFO, using Crust1.0 or Crust2.0 Vp in EARS gave results within 1.5 km of one another with comparable error bars. (Figure 3.5). This is most likely due to HK stacking being relatively insensitive to Vp used (Crotwell, 2007*)*.

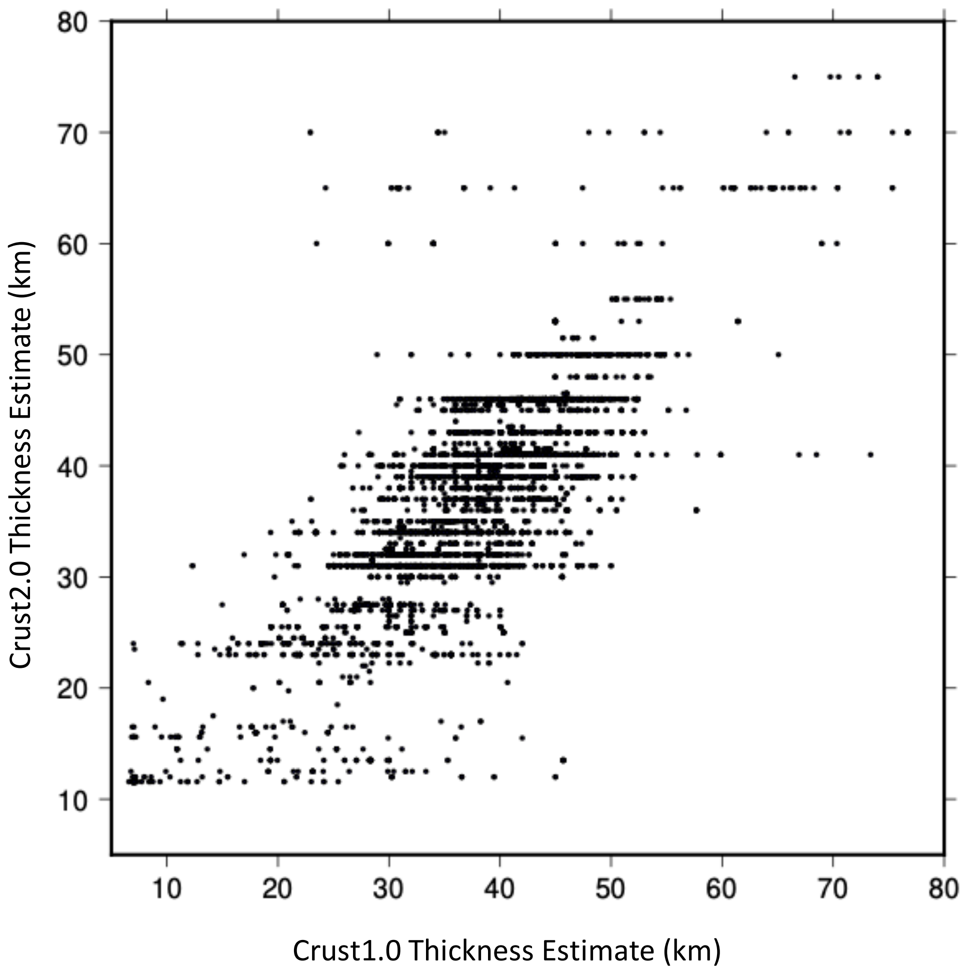


Figure 3.4: Plot of Crust1.0 vs Crust2.0 thickness estimates, for all stations.

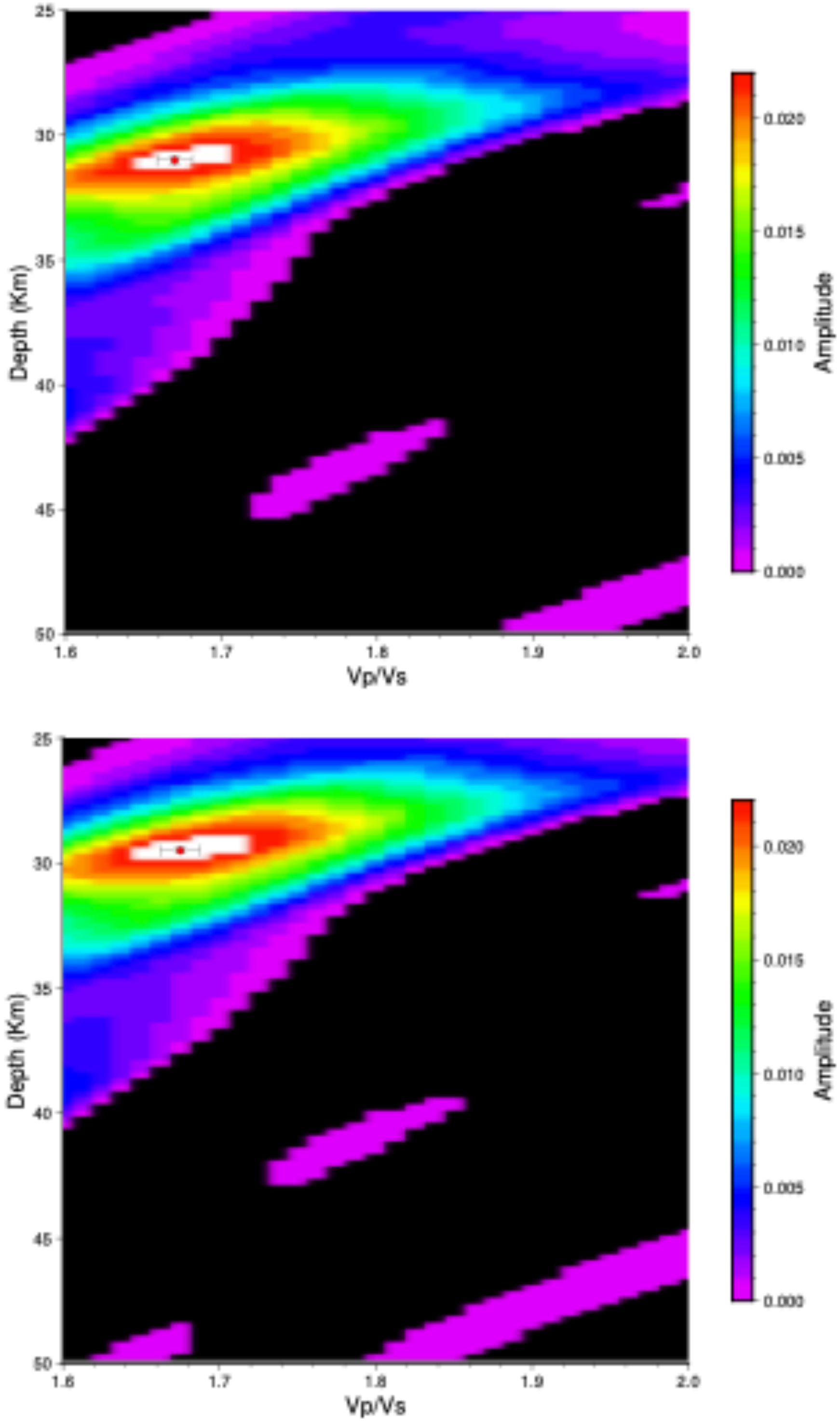


Figure 3.5: HK plots for PFO, comparing Crust1.0 (top) and current EARS (bottom), which uses Crust2.0 Vp estimates. Crust 1.0 Vp is 6.55 km/s with an estimate of 31 km. EARS (Crust2.0) has a Vp of 6.26 km/s and a thickness estimate of 29.5

Chapter 4: Extreme Station Observations

4.1. What and Where are the Extreme Stations?

An extreme station is defined by either having a thickness estimate greater than 55 km crust, or having an estimate difference of greater than 15 km than its neighbors (Figure 4.1). 55 km is defined as the thickest crust in Crust1.0 for the United States, and while not impossible, is generally not probable for many locations within the US. The goal with performing more in-depth analysis on these extreme stations is to determine possible causes for the extreme values or if they have a maxima that more closely matches the results of their neighbors since geological variances are not expected to be isolated at individual stations.

4.2. Percent Fit; Quality vs. Quantity of Events

When analyzing extreme stations, the first goal was to observe the impact of lowering the cut off for percent fit from 80% to 70% and above, which would allow more events in the stack. In a majority of extreme stations, there are secondary maximas that better match their neighbors. The goal was to have more events amplify the energy reverberating from the crust mantle boundary, making the secondary maxima become the new global maxima.

In approximately 45% of extreme value stations, lowering the percent fit improved the estimate, leading to the estimate being more compatible to the station's neighbors. An example of this is shown in Figure 4.2, with station 342A in Pineville, Louisiana. 342A has 3 events being used in EARS, and a thickness estimate of 61 km, but lowering the cut off to 70% allows for 39 events and a thickness estimate of 36.5 km, which is comparable to the neighboring stations

In 49% of stations, little to no impact was observed, and 6% of stations got further away from expected values. This means that in some stations with few 80% and above events, and questionable estimates, allowing more events into the stack may be a viable option, but should not be done as a blanket solution to all stations where the estimate is geologically improbable.

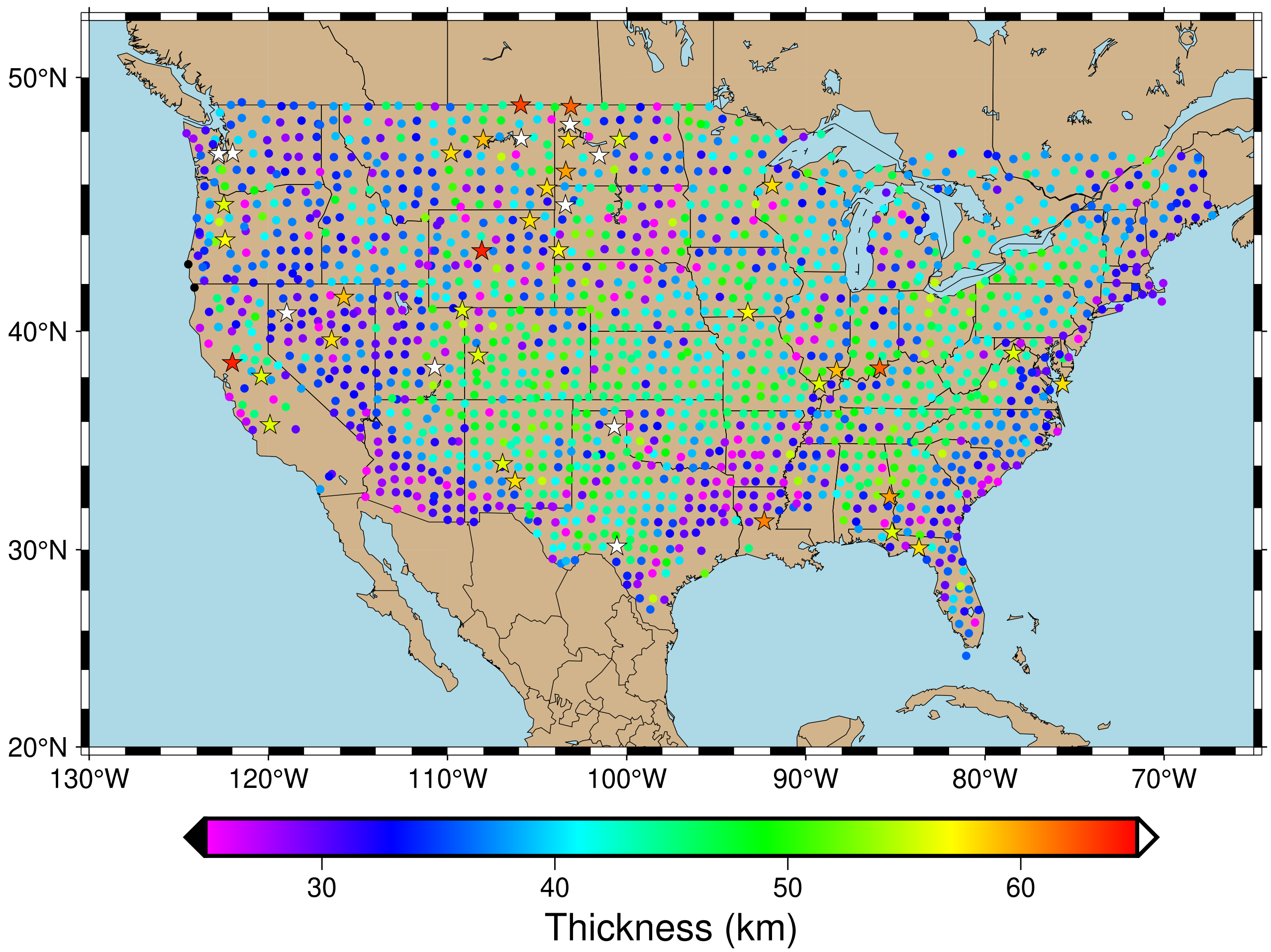


Figure 4.1: Map of stations with extreme thickness estimates, noted by a star in the color of their estimated thickness.

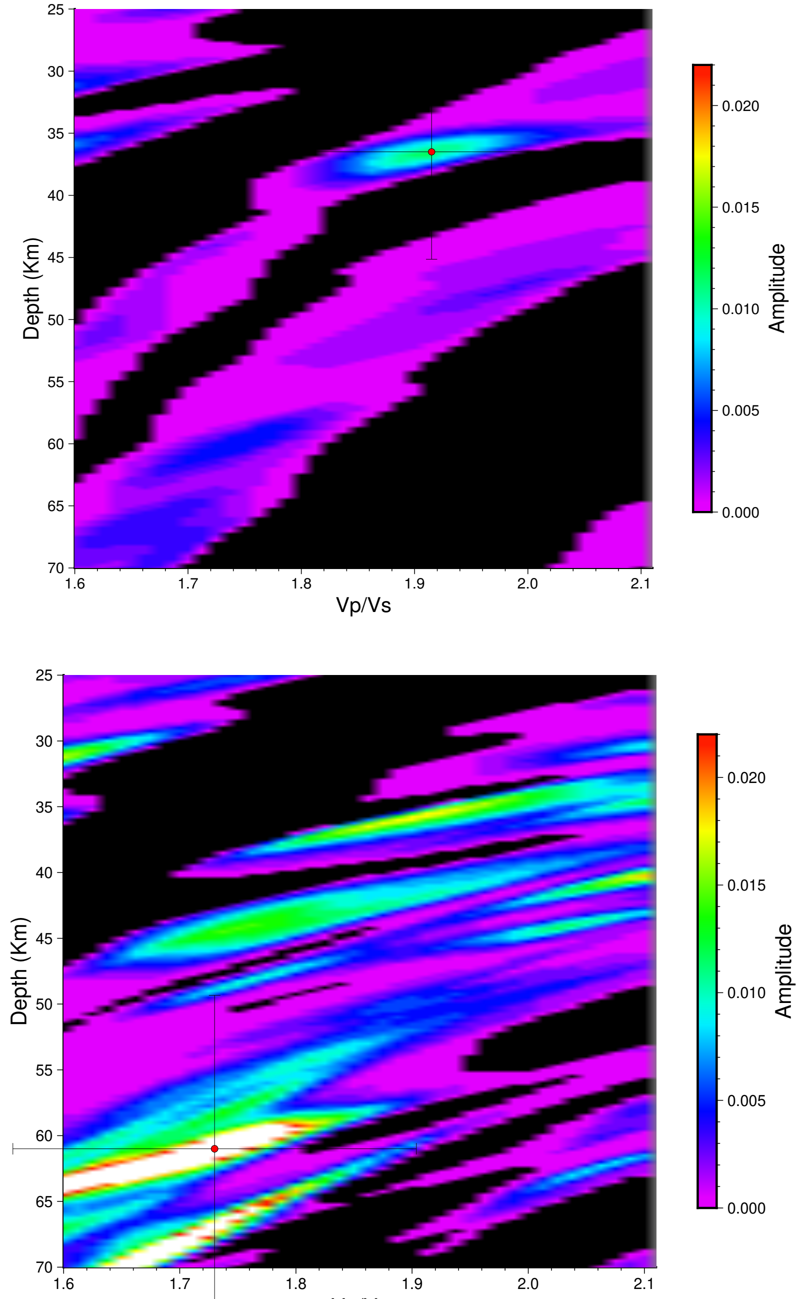


Figure 4.2: Station 342A, in the TA network. Top: HK stack using all events 70% and above; 39 events, 36.5 km and a standard deviation of 8.6 km. Bottom: EARS HK plot using an 80% fit cut off; 3 events, 61 km with a standard deviation of 11.6 km

4.3. Changing Vp Values and Limiting Vp/Vs solution Space

EARS requires a value for P wave velocity and uses Crust2.0's estimates of Vp. Since Crust2.0 uses 2x2 degree grid sizing, it has a lower resolution of Vp values for the globe then Crust1.0. While HK stacking is generally not sensitive to P wave velocity, it was possible that using Crust1.0's Vp would be enough to "flip" an estimate to a secondary maxima. This had little to no noticeable impact on any tested station's HK plot or estimate, however. This verifies how insensitive to Vp HK stacking is and with this in mind, there is no current cause to utilize Crust1.0's higher resolution Vp values. EARS Vp/Vs range is 1.6 to 2.1, which is a Poisson's ratio range of 0.179 to 0.353. This means that EARS allows Vp/Vs values which are outside of the range of common rocks. When observing Crust1.0's Vp/Vs values for continental crust, all values fell within 1.7 to 1.8 (Figure 4.3). Using that range, HK stacks were calculated for extreme stations. While this lead to a change in estimates in approximately 53% of stations, the results were simply plotting along the edge of maxima existing outside of the given range (Figure 4.4). This is not ideal as a new maxima is not being calculated, the estimate is just not being plotted, leading to a lack of reliability in the given result. It is important to note that a smaller standard deviation in this case is not indicative of more reliable results, as the solution space is simply excluding the variability within the data. This method also diminished the quality of data of robust stations without extreme values, as the expected answers were clipped from the plot. Larger ranges of Vp/Vs values are necessary to include the entire global maxima for results to be interpreted correctly.

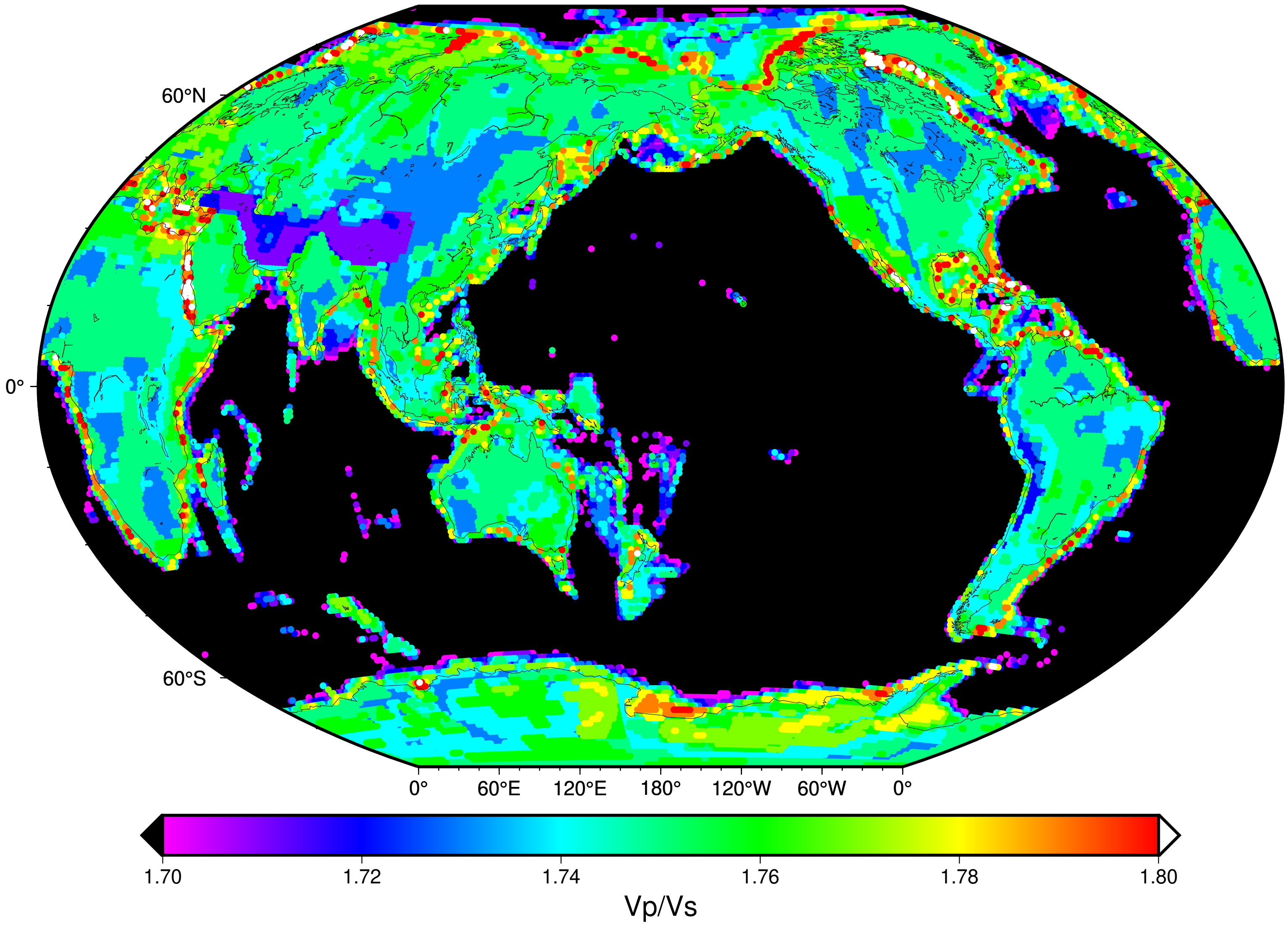
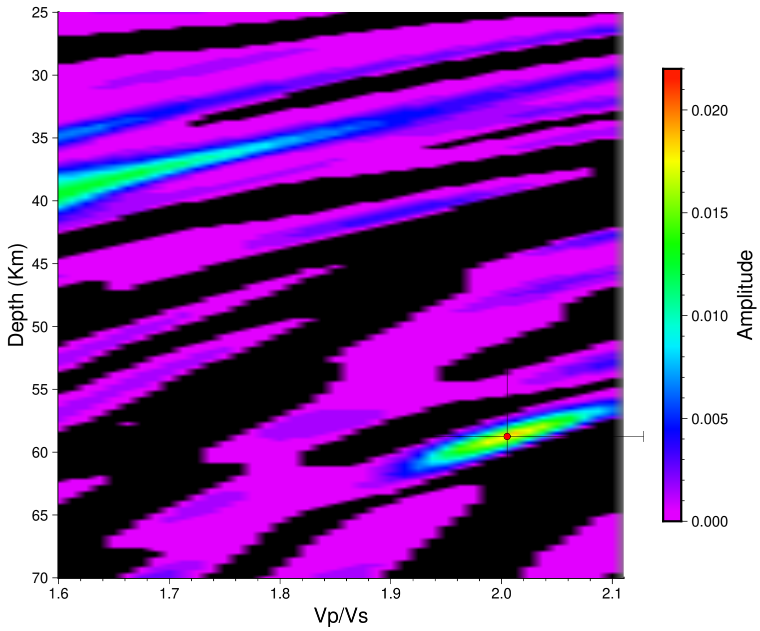


Figure 4.3: Global map of all Crust1.0 Vp/Vs values.



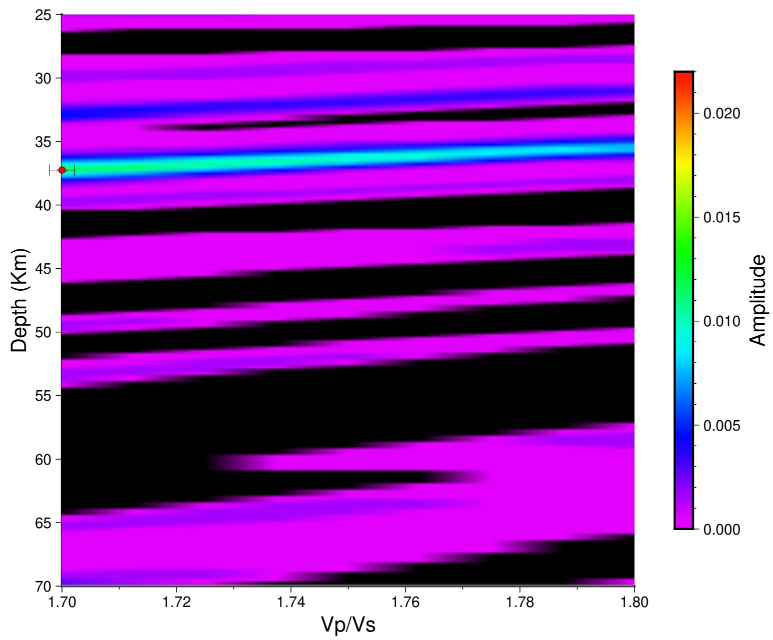


Figure 4.4: Station M11A HK Plots. Top: EARS HK plot, 58.7 km standard deviation of 6.276 km. Bottom: Constrained Vp/Vs plot, 37.25 km, standard deviation of 0.075 km. Top: EARS HK plot, 58.7 km standard deviation of 6.276 km.

4.4. Observing Tangential Component

As stated in the introduction, energy from seismic events is composed of a radial component and a tangential component. EARS uses the radial component when calculating HK stacks due to this method assuming a 1-D Earth model, where only the radial component should contain energy (Crotwell, 2007). However, receiver functions from tangential components can be calculated and used in an HK stack. In stations that behave as expected, the HK stack of tangential components should contain very small or negative amplitudes. In PFO, for example, the tangential HK plot contains negative amplitudes or amplitudes of zero, with a crustal thickness estimate of 54 km placed where no maxima is clearly defined (Figure 4.5).

However, in stations with extreme values, the waveforms did not behave this way, with the tangential component having larger amplitudes than the radial component's peaks. On these stations, compiling an HK stack on the tangential receiver functions created surprisingly reasonable estimates (Figure 4.6). Energy existing within the tangential component indicates the crust deviates from a simple 1-D Earth. While the use of tangential components is not suggested for EARS, it does present an interesting phenomenon. A likely candidate for this feature is dipping sediment layers below the stations (Owens et al., 1988). Dipping sediments can lead to increasing amplitudes in the tangential component, as wave reverberations continue to reflect off of the dipping surfaces. A means of reducing the impacts of dipping layers within automated broadband seismology is essential but is beyond the scope of this thesis.

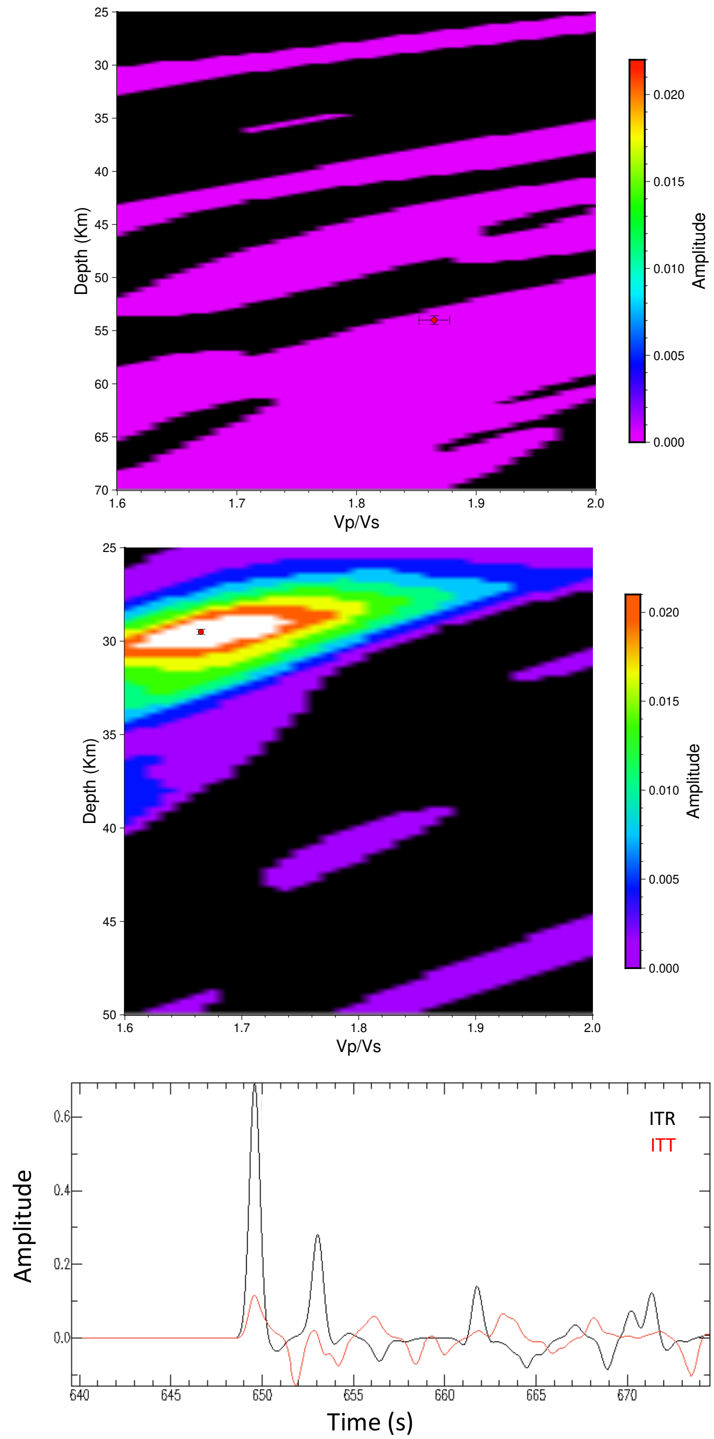


Figure 4.5: Top: Station PFO HK plot using tangential receiver functions, H: 54 km, K 1.865 Middle: EARS HK plot using radial receiver functions, H: 30 km, K: 1.68. Bottom: waveform from event 2006-319-11-14-13, with radial receiver function in black and tangential in red.

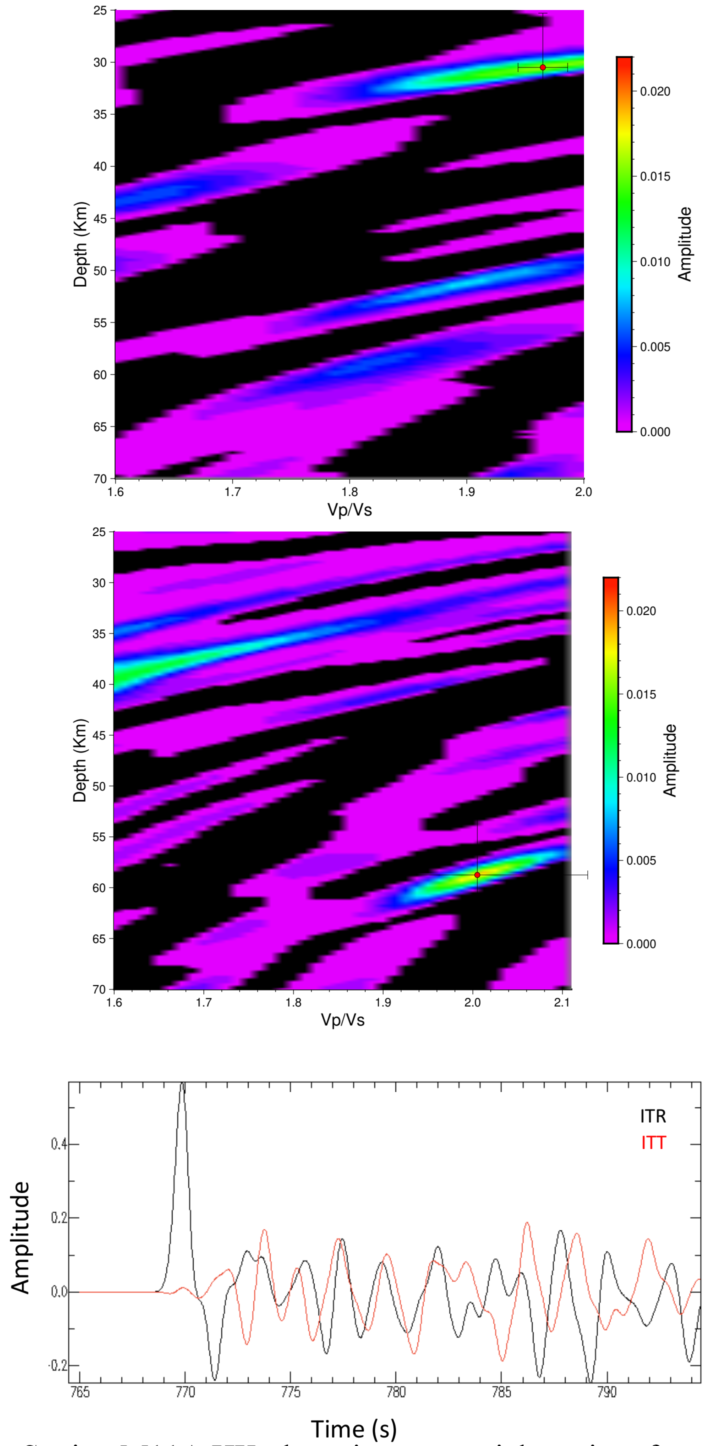
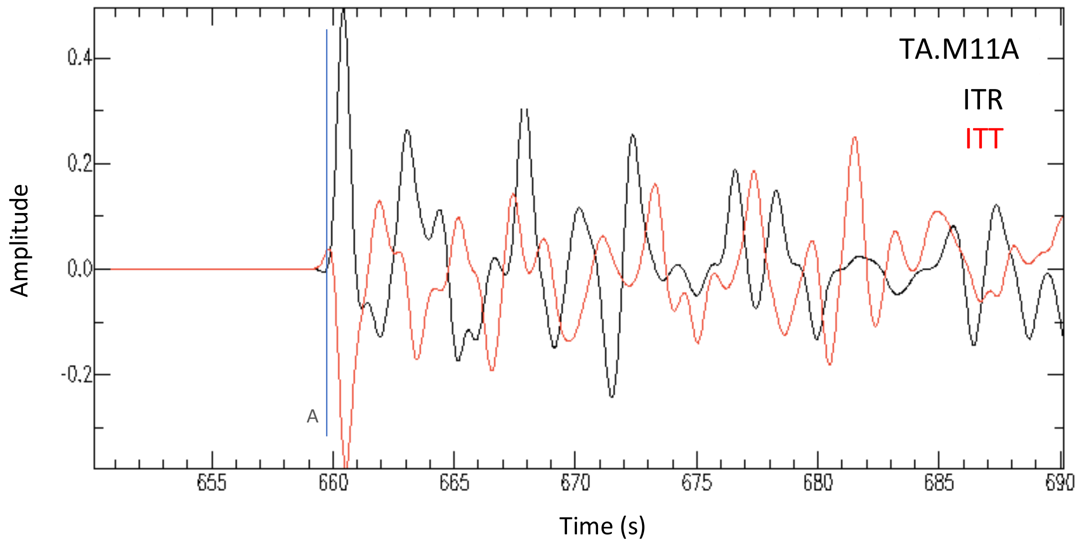


Figure 4.6: Top: Station M11A HK plot using tangential receiver functions, H: 30.5 km, K: 1.965. Middle: EARS HK plot using radial receiver functions, H: 58.77 km, K: 2.005. Bottom: waveform from event 2008-130-21-51-29, with radial receiver function in black and tangential in red.

4.5. Primary Arrival Offset (PAO)

Every receiver function in EARS contains the expected arrival time, in seconds, of the zero lag correlation between the radial and vertical component. This expected arrival time signifies where the zero lag of the radial and vertical components should land, in a non-complex Earth. This should be the first peak in the waveform data. Ideally, the difference between the actual and expected primary arrival, should be very small or zero. In stations such as PFO, expected arrival nearly always matched actual arrival, whereas in many of the extreme stations, the expected arrival varied from the actual (Figure 4.7).

The average difference between the expected arrival and actual arrival was calculated for all stations within the TA and US networks that fell within the continental United States. For the average primary arrival offset (PAO) value to be reliable for a given station, it should be calculated from a variety events at various azimuths. This is due to the fact that the crustal structure could vary depending on the direction the event arrives from, which would impact the offset. With this consideration, all stations with less than 10 events were removed from the PAO analysis. From there two groups of stations were determined; "good" and "questionable". To determine which category a station belonged, several thresh holds were compiled. For the purpose of PAO analysis, a "good" station had a thickness standard deviation of less than 5 km, a thickness estimate of less than 55 km, and matched within 15 km thickness, its neighbors. Conversely, a station was considered questionable if it failed any of these criteria.



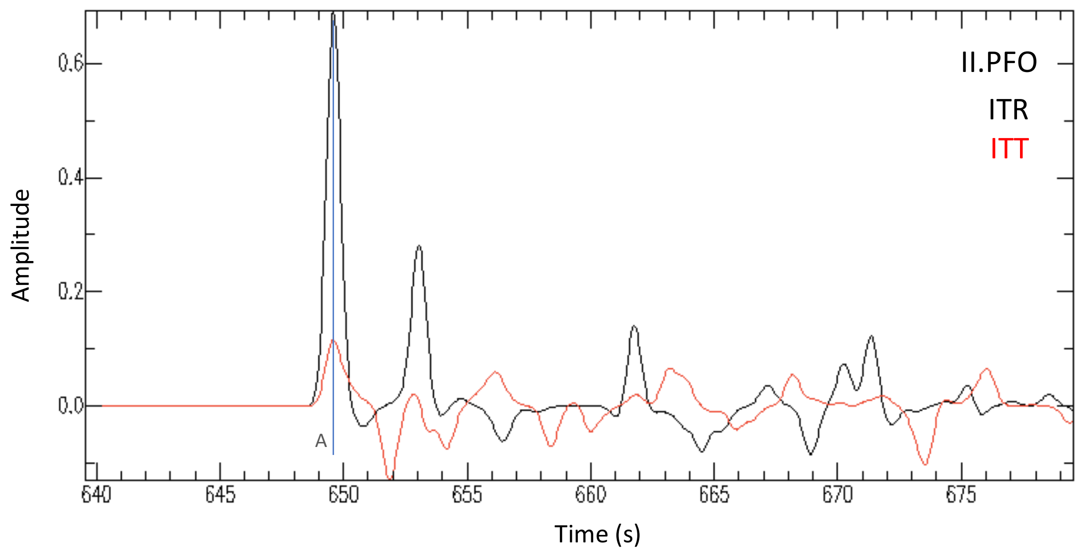


Figure 4.7: Top: Event from station M11A in red, with expected arrival noted by line A. Actual occurs approximately one second later.
Bottom: Event at PFO, where expected arrival is noted by line A, where actual arrival does occur.

Note the larger amplitudes of the tangential in station M11A.

A standard deviation of 5 km was chosen to due to this being where a majority of standard deviations in the US and TA networks fell, along with being below the range of standard deviations observed in extreme value stations. Note in this case, a “good” station merely checks all mentioned boxes and no assumption is currently being made about the quality of data or results by that title.

When observing the distribution of average PAO per station, approximately 58% of “good” stations had an average PAO smaller than 0.25 seconds. Approximately 30% of questionable station’s had average PAO falling below 0.25 seconds, meaning 70% of stations have an offset larger than 0.25seconds (Figure 4.8). With this consideration, and observing the distribution of the average offsets, having a PAO greater than 0.25 seconds appears to be another flag one could observe at a given station to make a determination on the reliability of a station’s estimates.

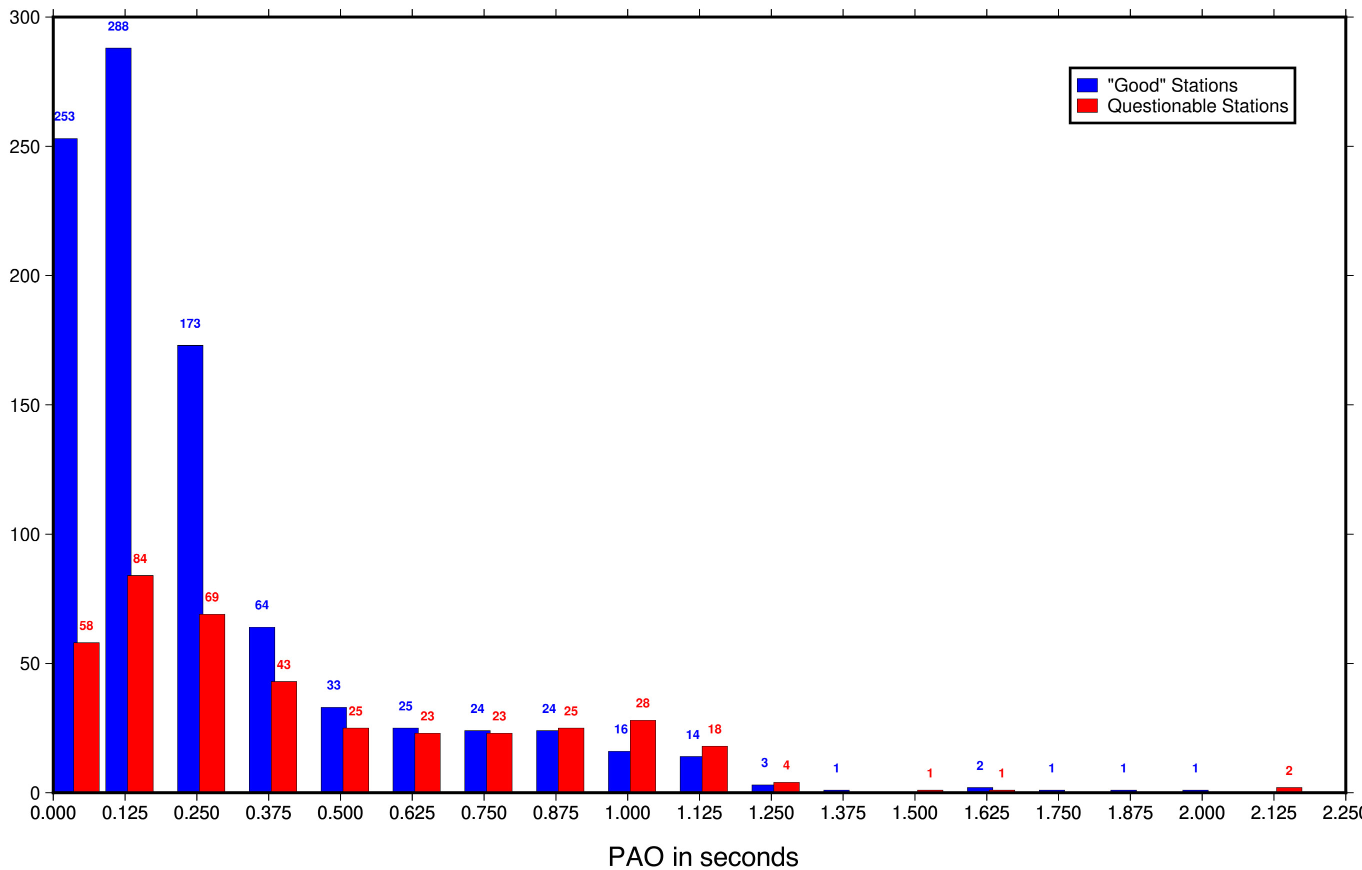


Figure 4.8: Distribution of PAO for all continental United States stations in the US and TA networks, that have greater than ten events.

Chapter 5: Physiographic Boundaries visible in EARS

When observing the reliability of EARS, comparing to known and observed physiographic boundaries was important, as to see what known features were visible in EARS results. These boundaries include features such as basins, plains, and ranges. Stations' thickness estimates, Vp/Vs ratios and average PAO were plotted against physiographic boundaries within continental United States, using TA and US networks. Some physiographic boundaries were more pronounced in certain datasets, but absent in others, while a few boundaries were clearly visible in all three maps. (Figure 5.1, 5.2). Surprisingly, the Mid Continental Rift zone was not clearly visible in any of the maps. However, the Williston Basin, Mississippi Embayment and coastal plains were evident in all three datasets. By observing each map, characteristics of specific formation types can be inferred. Basins and plains, especially are very clear in all three maps, with higher Vp/Vs ratios, larger PAOs, larger numbers of extreme stations, and widely fluctuating crustal thickness values. While not being remarkably visible in the PAO and Vp/Vs maps, the Colorado Plateau and Basin and Range are well defined within the crustal thickness estimates map.

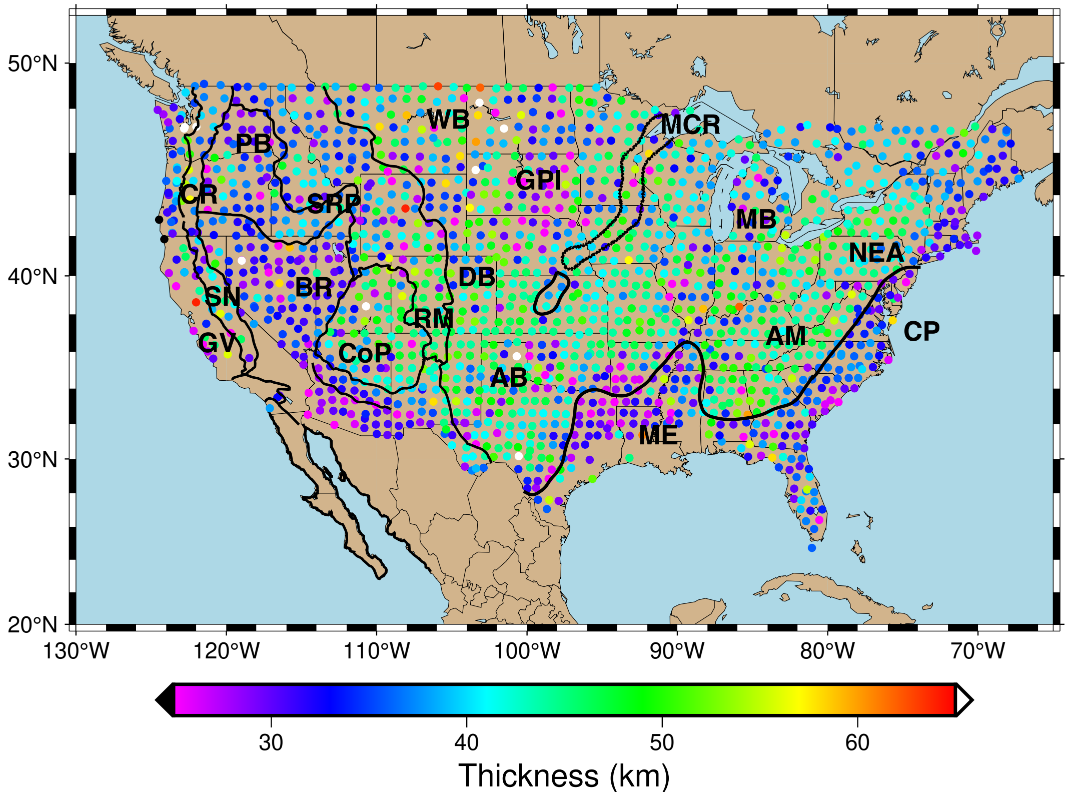


Figure 5.1 EARS thickness physiographic boundary map of the United States using stations in the TA and US networks.
Physiographic boundaries are noted by solid black lines and are the same for all maps. The boundaries abbreviations are noted in the top map and are as follows:

AB	Anadarko Basin	CP	Coastal Plains
DB	Denver Basin	CR	Cascade Range
GV	Great Valley	GPl	Great Plains
MB	Michigan Basin	MCR	Mid-Continent Rift
PB	Pasco Basin	ME	Mississippi Embayment
WB	Williston Basin	NEA	Northeast Appalachians
AM	Appalachian Mountains	RM	Rocky Mountains
BR	Basin and Range	SN	Sierra Nevada
CoP	Colorado Plateau	SRP	Snake River Plain

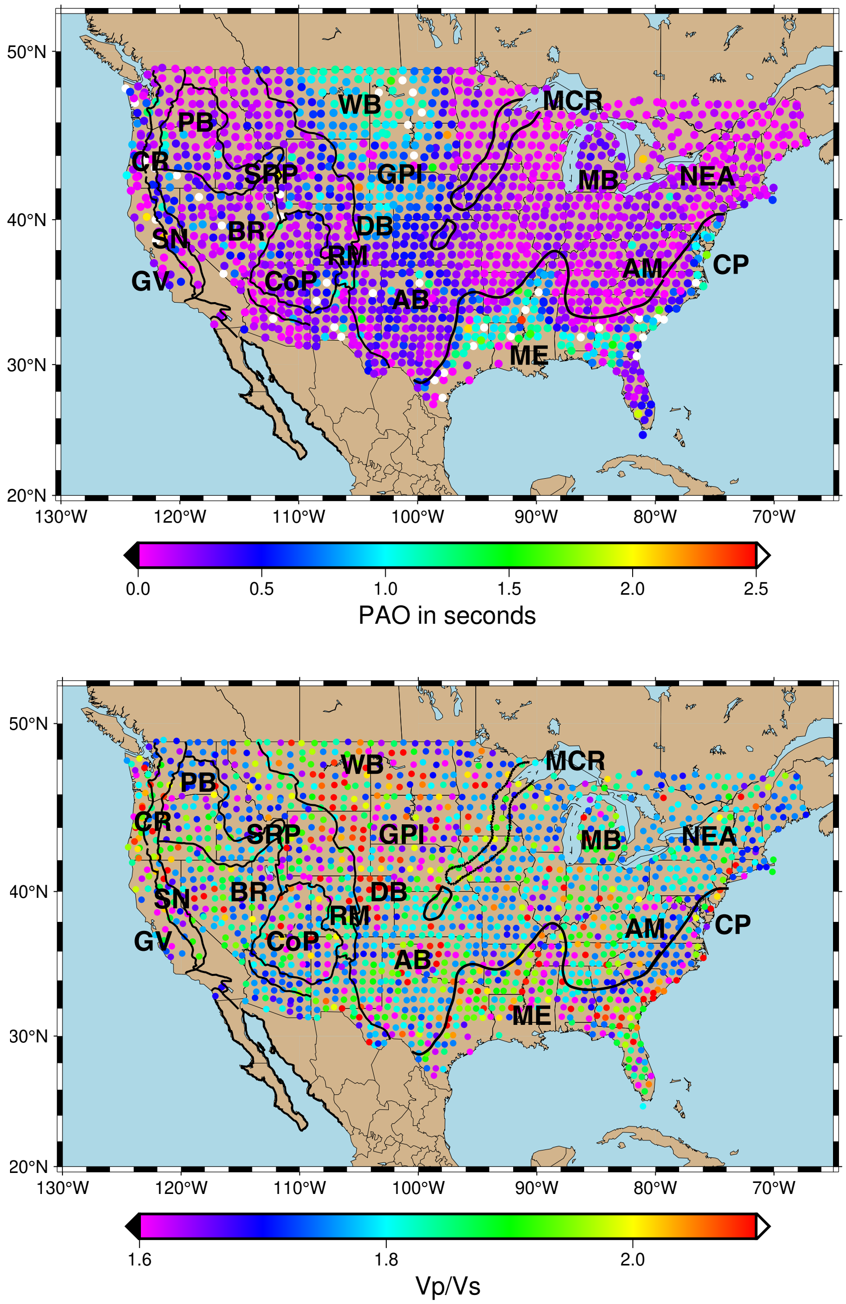


Figure 5.2 Physiographic boundary map of the United States using stations in the TA and US networks showing average PAO (top) and EARS Vp/Vs (bottom). Physiographic boundaries are noted by solid black lines and are the same for all maps. The boundaries abbreviations are noted in figure 5.1.

Chapter 6: Recommendations to IRIS

6.1. Metadata Inconsistencies

6.1.1. Incorrect End times in SAC Files

Downloaded data from EARS comes in the form of Seismic Analysis Code (SAC) files, which have filled header values for event information such as start time, end time, magnitude, and expected primary wave arrival. EARS creates these files, and fills the headers with relevant data. These headers are used by relevant programs that are used to process waveform data. During analysis, it was discovered that EARS is filling the end time header incorrectly. The end times are the length of the waveform data in seconds, while the start times are the beginning the of the waveform data, but shown in seconds after the event's origin time, which is common practice. This leads to end time values that are smaller than the start times in all 1.4 million events in EARS. The solution to this is adding the current end time value to the start time, to produce the correct end time. This should be resolved to ensure accurate reflection of data along with guaranteeing the files are compatible with all seismic analysis programs.

6.1.2. Erroneous Magnitudes

One possible impact on the reliability of estimates to be considered is the magnitude of the events in the stack. EARS has a cut off of magnitude 5 or greater for the events that are able to be used. The goal was to determine if there was a correlation

between percent fit and magnitude, and whether a cut off of 5 and above was reasonable. However, upon a plot based on percent fit versus magnitude, it was discovered that the metadata for each event contained erroneous magnitudes, with a large quantity falling below 5 magnitude (Figure 6.1). This led to an inability to perform any robust analysis on magnitude impact and percent fit cut offs. EARS utilizes a best fit magnitude provided by the IRIS DMC, which is not currently available in the SAC files. Moving forward, EARS should ensure the SAC files available in their database also contain the appropriate magnitude used in IRIS DMC.

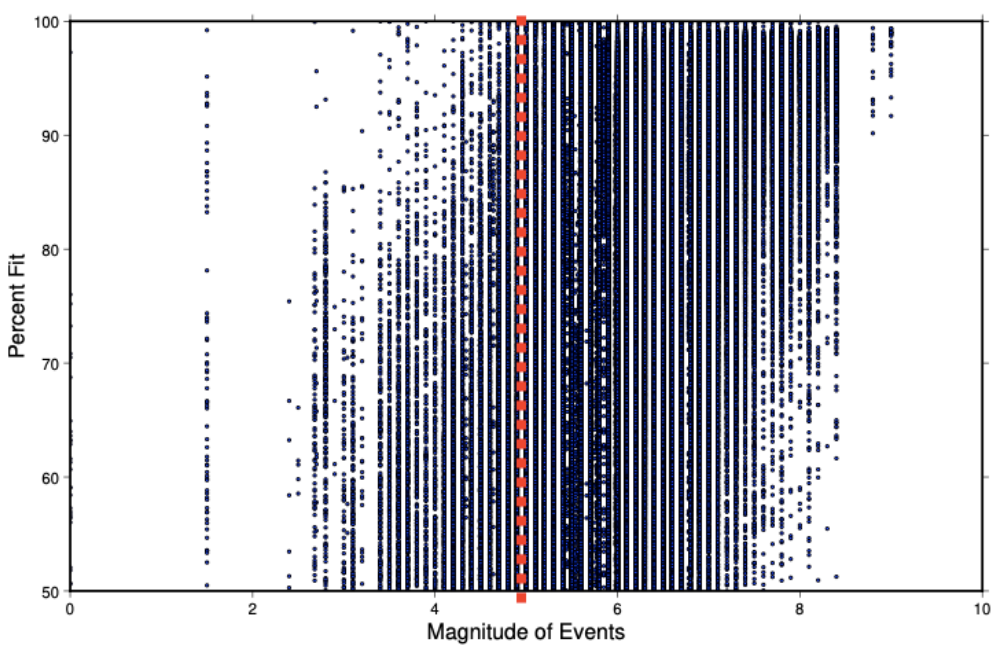


Figure 6.1: Plot of all events' magnitude vs percent fit. EARS cut off point for magnitude, noted by red line at magnitude 5

6.2. Summary File

When one downloads data from EARS, there is a summary file that contains all current stations along with their locations, estimates and standard deviations. This is a useful tool when examining the dataset, however there is a concern one should be aware of when utilizing this file. Approximately 2,000 temporary stations have mislabeled network codes, that lack the years they were in operation. Networks such “XM.99” and “XM.95” are unpacked into directory “XM”. This leads to issues when attempting to do automated data analysis using Python or GMT, when directory and name patterns are essential.

Additionally, since EARS has cutoffs such as 80% fit and a maximum of 200 events that can be used in any stack during the automation process, but stores all events, there is no realistic way to know how many events are available for any given station. For example, station PFO has 592 events that are over 80% fit but that information is not readily available, as the number of events shown is still 200.

Being aware of these limitations is helpful in efficiently using the EARS database, depending on what analysis a person would want to complete. However, it is a reasonable recommendation to EARS to attempt to include this type of information in the summary file.

6.3. Allowing 70 Percent Fit Events

Since lowering the percent fit was effective in 45% of tested stations, it seems reasonable to have the option to allow lower percent fit events to be placed into the stack. For stations with less than 10 events, the option to lower the percent fit cut off to 70 percent and above could prove beneficial in providing more robust results in stations that lack sufficient data. This data is already stored in EARS, but not currently able to be used in the crustal property estimates, through the web service.

6.4. Flags Indicating Station Reliability

When reviewing a station's crustal thickness and Vp/Vs estimates on EARS, through IRIS DMC data products, there is no indication on reliability from one station to the next. When considering the heterogeneity that exists throughout EARS, it would be reasonable to have a system assessing a station's reliability based on a set of parameters. It is recommended assigning a rating for each of these five parameters: number of events, standard deviation, average PAO, thickness values compared to neighbors, and extreme thickness values compared to Crust1.0. Since extreme values are dependent on geographical location, providing a comparison to a station's designated Crust1.0 thickness, along with comparing it to an EARS average of the surrounding stations allows for assessment using location specific estimations. These parameters also allow for external and internal comparisons for calibration.

While residual complexity is an available value on EARS, and can be an indication of result reliability, it is not included in the scoring parameters. This is due to the strong correlation between residual complexity and standard deviation (Figure 3.1). Including this score would only serve to "pad" stations with smaller standard deviations, while disproportionately diminishing stations' scores with larger standard deviations.

This study has shown that there is no single measure for all stations, that can establish how much confidence can be placed in an estimate. However, compiling all five parameters could lead to a cohesive measure of reliability which could work for all EARS results. The recommended scale for each parameter would be 1 to 3. A score of one would mean performing poorly in that specific category, while a three would be the highest score and indicating that the parameter is being met. The greatest overall score a station could receive would be 15, which would entail that a station is producing robust results, due to meeting the standard in every area (Table 6.1). Using this system, performing poorly in one area does not necessarily indicate a station is producing unreliable results, but rather allows us to give a broad view of data trustworthiness. When applying this rating system, the TA and US networks within the continental United States, the results are promising. 25.17% of stations had a perfect score of 15, with 51% of all stations scoring 14 or above (Figure 6.2). The Mississippi Embayment, West coast, Eastern coastal plains and Williston basin appear contain a majority of the low scoring stations. This is likely due to dipping sediment layers, water saturated sediments, and the complex tectonic structure in the Western United States.

Table 6.1: Reliability Scoring guide for EARS estimates

Parameter	**Score: 1**	**Score: 2**	**Score: 3**
Thickness Standard Deviation	Greater than 5 km	2 to 5 km	Less than 2 km
Number of Events	Less than 10 Events	10 to 20 events	More than 20 events
Average PAO	Greater than 0.25 seconds	0.2 to 0.25 seconds	Less than 0.2 seconds
Extreme Values compared to Crust1.0	Greater than 20 km for given region's Crust1.0 values	Greater than 10 km for given region's Crust1.0 values	Within 10 km of a region's Crust1.0 values
2x2 degree Average Thickness Comparison	Estimate is more than 15 km different than area average	Estimate is more than 10 km different than area average	Estimate is less than 10 km different than area average

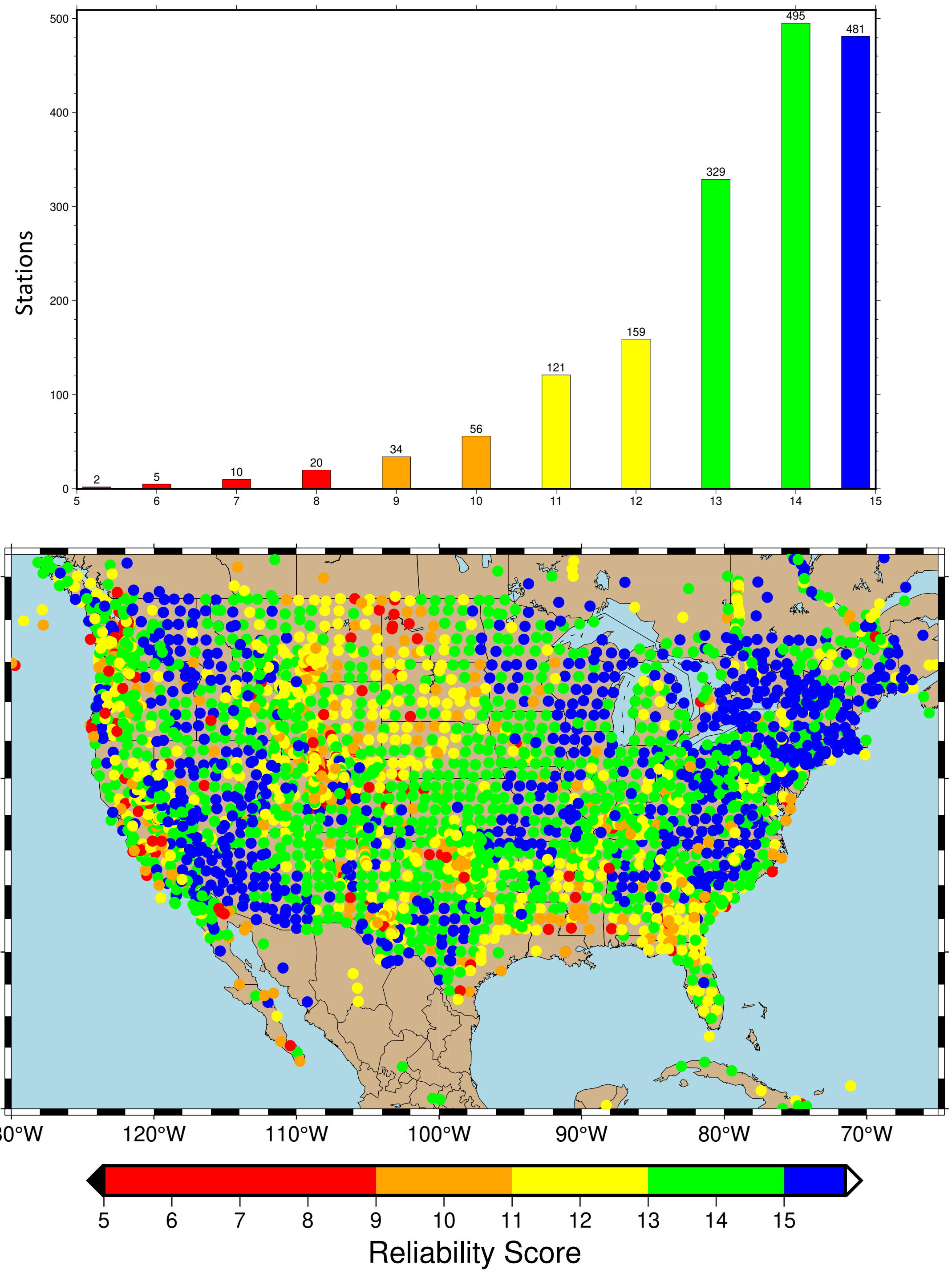


Figure 6.2: Stations from networks US and TA, in the continental United States. Distribution of reliability scores (top). Map of stations with their respective reliability score (bottom).

Chapter 7: A User's Guide to EARS

7.1. EARS vs Crust1.0

While there are several crustal property estimations available to choose from it is important to acknowledge the strengths and limitations of various methods. Here, Crust1.0 was used as a comparison to assess EARS results. Crust1.0 provides a comprehensive grid of designated crustal property estimates based on tectonic settings and an eight-layer crustal profile (Laske et al., 2013). The benefit to this is estimates are assigned to every 1x1 degree cell, providing crustal property estimates, globally (Figure 7.1). However, Crust1.0 was developed to correct surface wave observations for shallow structure, due the crust's impacts on seismic observations (Laske et al., 2013). While Crust1.0 is very effective for its intended purpose, its estimates remain set, and assume homogeneity within every grid square. EARS has a different goal and collects event information as it occurs, producing an estimate of crustal properties that can fluctuate over time, and allows for heterogeneity to exist for every station. Conversely, because EARS is based at stations, it does not provide any information for crustal properties where there are no stations, and can only be as good as the quality of the data a station is collecting.

7.2. How to know when to trust EARS?

When viewing a station's HK plot, it is not immediately clear whether the estimate is reliable. Perhaps it has a large standard deviation, but appears to match its neighbors, can it still be trusted? To answer this question, stations need to be viewed holistically by observing all the given parameters. The station PFO has been cited several times as a baseline for producing robust estimates. This station has over 500 events, a small standard deviation of 0.12 km, and 97.5% of its PAOs fall below 0.20 seconds. PFO's thickness is 29.5 km, which is expected for its location and matches many of its neighbors. PFO has a reliability score of 15, even while existing in a tectonically complex region, with other neighboring stations producing extreme values. This is to show that looking at a station holistically provides more insight than any individual value.

If a station's reliability score is below an eight, the results likely require further inspection; possibly by examining other local maxima that exist within that station's HK plot, or allowing more events into the stack by lowering the percent fit. It is important to not make assumptions based solely on a thickness standard deviation, as standard deviation is not implied as a deviation from "truth" but variations, or lack of variations within the waveform data.

7.3. Look at the Big Picture

The most effective way to utilize a data product such as EARS is to consider entire regions, rather than individual stations. If a single station estimates a 60 km thick crust in the center of a region where 30 – 40 km is expected, the results should immediately be in question. However, when several stations in a region are producing similar answers, that is a good indication of something observable occurring within the crust. Across the continental United States, EARS can capture many largescale physiographic boundaries and give insight to crustal properties that are consistent with each other; and while individual outliers do exist, they are but one dot in a bigger picture.

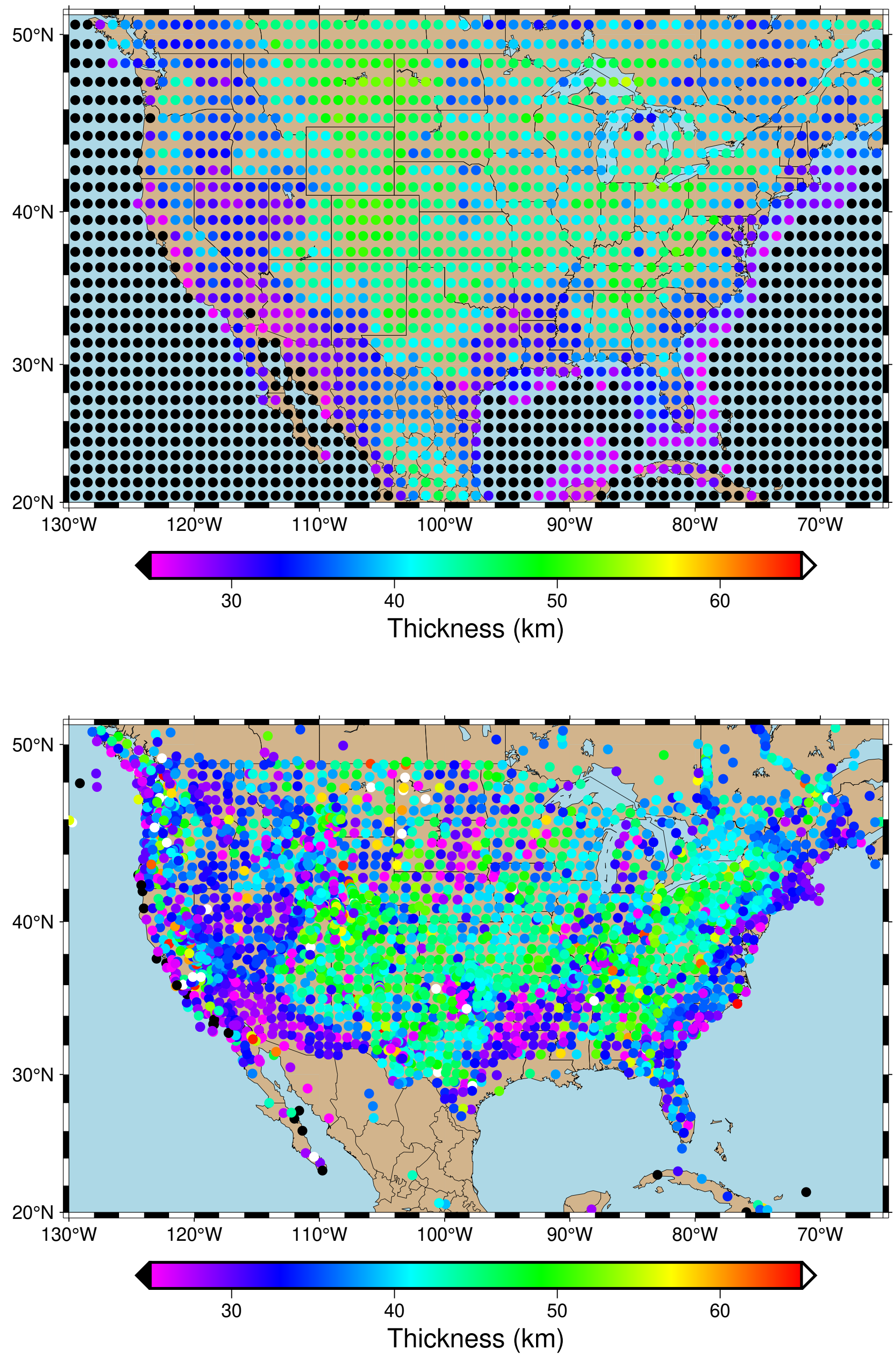


Figure 7.1: Comparison of Crust1.0 thickness estimation map (top) and EARS thickness map (bottom) for the continental United States.

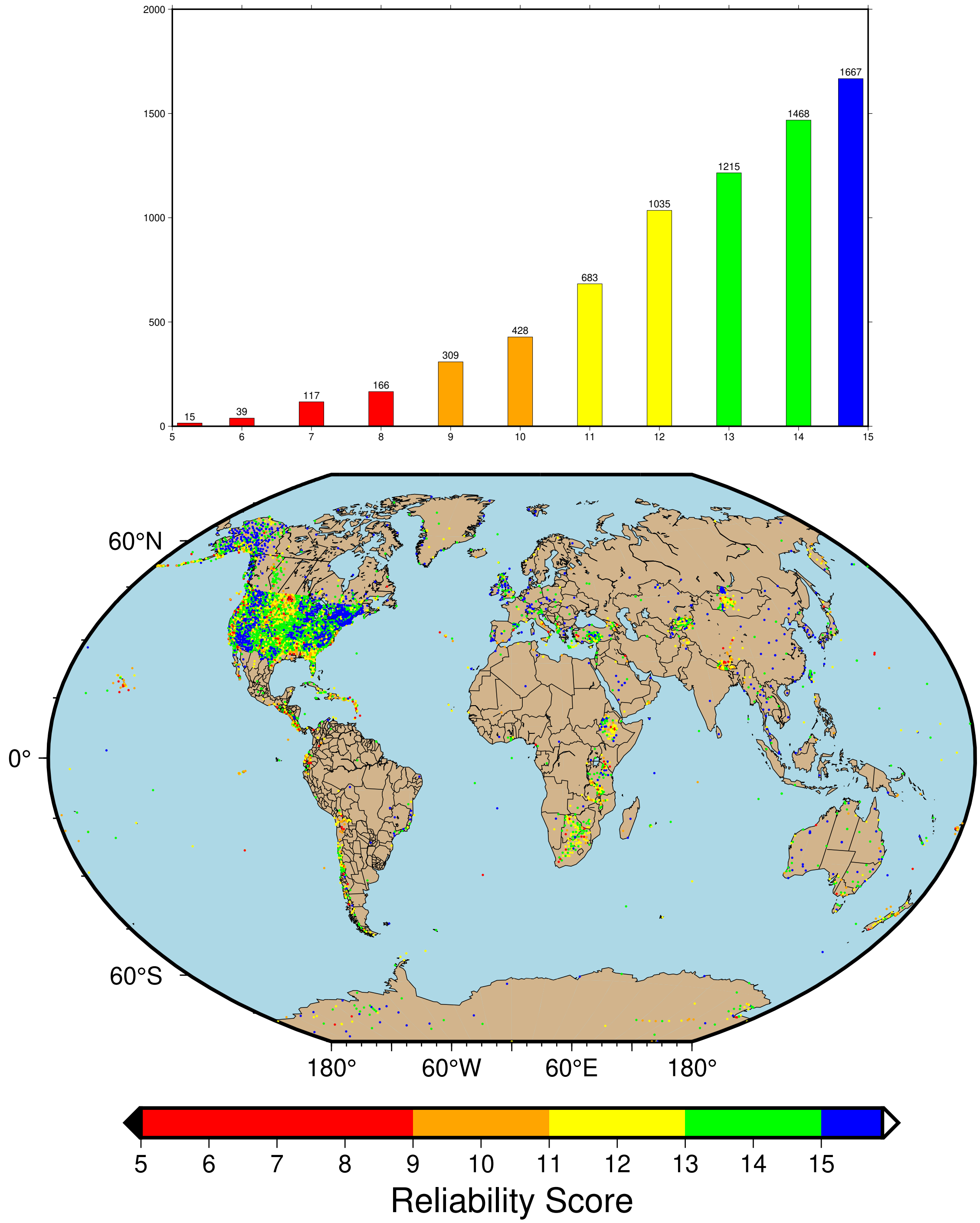


Figure 7.2: All stations contributing to EARS. Distribution of reliability scores (top). Map of stations with their respective reliability score (bottom).

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