REGIONAL CHARACTERIZATION FROM JOINT INVERSIONS OF GEOPHYSICAL DATA

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ABSTRACT

A continuing problem in the monitoring of a Comprehensive Nuclear-Test-Ban Treaty is the development of three-dimensional models of the earth's velocity structure which have sufficient resolution to provide accurate locations of seismic events and allow the use of waveform modeling techniques at regional distances. In most cases these velocity models must be estimated on the basis of insufficient data, as both the types and the coverage of the geophysical information is usually quite limited. We have been trying to develop approaches to this problem that use all of the available data in a consistent manner and that obtain solutions to the inverse problems, which are as unrestricted as possible. The data types included so far are structural information from regional geology, regional gravity data, receiver functions at individual seismic stations, and travel times from local and regional seismic events. The inversions for velocity structure are being performed with a genetic algorithm, an efficient stochastic optimization scheme, which mimics Darwinian natural selection in order to find the best fitting models. We are currently applying these techniques to two regions, the Mendocino triple junction region of northern California and the South Island of New Zealand.

In the Mendocino region, receiver functions are available at 6 broad band stations, and it is possible to resolve both the crustal structure and a subducting Gorda plate as having a dip that gradually increases from 3 to 22 degrees with distance from the coast.

In New Zealand, receiver functions are available from the portable broad band stations of the Southern Alps Passive Seismic Experiment (SAPSE). The quality of the data is less than that of the Mendocino region, but it is still possible to resolve crustal thickness' that range between 20 and 40 km which appear to correlate well with distance from the Alpine Fault. Considerable attention is given to the most difficult aspects of these types of problems, the general non-uniqueness of the results, the effects of dipping boundaries, and the effects of anisotropy.

Key Words: seismic velocities, regional structure, inverse problems

OBJECTIVES

The scope of this research effort is concerned with the development of an improved understanding of methods for locating and characterizing seismic events in a heterogeneous earth. The general objective is to investigate how improved models for the generation and propagation of elastic waves can help in the evaluation of methods and models currently being used. The work statement for the research contains two primary tasks:

1) Continue the development of analytical and numerical techniques capable of modeling the physical processes that cause the generation of elastic waves by seismic sources. Also continue the development of three-dimensional models of the earth's velocity structure, which have sufficient resolution to provide accurate locations of seismic events at regional and teleseismic distances.
2) The modeling capability will be validated against existing data bases and any new data which can be acquired by taking advantage of targets of opportunity to perform broad band recording experiments.

During the past year research was conducted in a number of areas related to the objectives listed above, which can be grouped under the following general descriptions:

1) Effect of damage on explosion generated elastic waves
2) Scaling relationships for explosions and earthquakes
3) Use of genetic algorithms in geophysical inverse problems
4) Calculation of waveforms in three-dimensional media
5) Three-dimensional regional velocity structure

This paper will be concerned with the third and fifth topics, the study of improved methods of constructing three-dimensional models for use in regional monitoring.

RESEARCH ACCOMPLISHED

Our recent research on regional velocity structure has concentrated on developing inversion methods that explore the entire range of possible models and permit use of all available geophysical data. Some of the results of this research are described below using the Mendocino area of California as an example. This is a good test of our approach, as it is a region with a fairly complicated structure involving plate boundaries, a triple junction, and a subduction zone. The results included in this paper are primarily those obtained by the analysis of receiver functions obtained at seismographic stations operating in the Mendocino region.

The complex plate geometry of the Mendocino Triple Junction (MTJ) is the focal point of northern California tectonics. Bounded by strike slip faulting to the West and South and subduction to the North, the junction itself has been moving to the North at a rate of approximately 5 cm/yr for the last 5.5 million years (Atwater, 1970). This northward migration (and the oblique convergence of the Juan de Fuca/Gorda Plate) are responsible for many of the significant tectonic events in north America, including (1) volcanism in the Northern Coast Ranges, (2) a broad zone of faulting and deformation in the Coast Ranges, and (3) extinction of arc volcanism to the North of the MTJ (Benz et al., 1992).

The North American Plate in the region of the MTJ is an accretionary complex of Mesozoic to Cenozoic origin (the Franciscan, manifesting itself in the Coast Ranges and Klamath Mountains) which is overlain by the Eel River Basin, a sedimentary forearc basin of Cenozoic origin (Beaudoin and Magee, 1994). Velocities in these crustal units are believed to be relatively uniform, in the range of 5.5-5.8 km/s in the West and 6.0-6.5 km/s in the East (Beaudoin and Magee, 1994; Benz et al., 1992). The subducting Gorda Plate is believed to vary in thickness from 7 km at the Southern end of the MTJ to 10 km in the North, decreasing in velocity from 6.7 km/s to 6.2 km/s at the same time (Beaudoin and Magee, 1994).

Figure 1 is a schematic cross section of the standard model for the tectonic interaction in Northern California as proposed by Benz et al. (1992). The cross section is assumed to be valid for the region between 40 and 41 degrees latitude. The dip associated with the subducting Gorda Plate is a matter of much contention. The most reliable estimates come from east-west cross sections of seismicity, which define a Benioff zone that dips 10^{O} to the east at the coast and up to 25^{O} below the Southern Cascades. Estimates of the velocities V_1, V_2 and V_3 are not as reliable as the estimates of Benioff zone dip. V_1 is likely the least uncertain, typically in the range of 6.3 to 6.5 km/s. V_2 is found to be as low as 6.7 km/s

(Beaudoin and Magee, 1994) and as high as 8.0 km/s (Benz et al., 1992), and the underlying mantle velocity V_3 is usually estimated to be from 8.0 to 8.2 km/s.

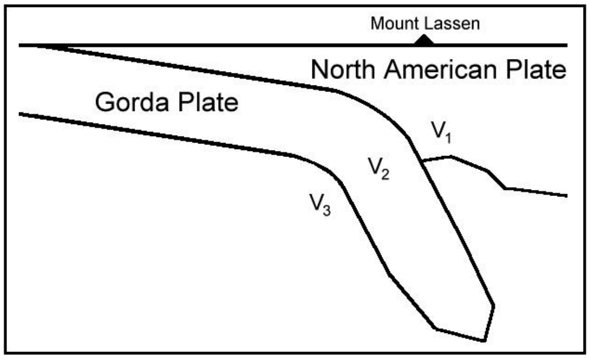

Figure 1. Schematic east-west cross section of standard model for the tectonic interaction in Northern California as proposed by Benz et al. (1992) (not to scale).

Focal mechanisms and seismicity patterns imply a change in the orientation of stress on the Gorda Plate from compression in the North-South direction to down slab extensional beyond 236^O east (Dicke, 1998). An obvious consideration with a model in which $V_1 < V_2 < V_3$ is the lack of a driving force for this type of subduction. If $V_2 < V_3$, the Gorda Plate should also be less dense than the underlying mantle material and therefore more buoyant. It is possible that compressional forces associated with spreading from the Gorda Ridge are driving the subduction. In this case there should either be a thickening of the Gorda Plate as it is being subducted or some type of imbrication. Benz et al. suggest that the slab is imbricated in the MTJ region resulting in accreted slab fragments under the North American Plate, but Verdonck and Zandt (1994) find the plate to be intact.

Receiver functions are calculated for 7 teleseismic events recorded at five northern California Broadband stations in the Berkeley Digital Seismic Network (BDSN) (see Table 1). The stations and their spatial relationship to the MTJ can be seen in Figure 2. The teleseismic data used in this investigation consist of 7 events of magnitude 7.0 or greater between -15 and -28 degrees latitude and -173 and -179 degrees longitude (see Table 2). The 7 South Pacific events have travel paths approximately perpendicular to the zone of convergence in the MTJ region.

The data, sampled at 0.05 s, is filtered to remove microseismic noise below 0.15 Hz, cosine tapered and 25% zero padded before being deconvolved with a Gaussian filter coefficient of $\alpha = 2.0$ to produce both radial and tangential receiver functions for each station-event. The stacked receiver functions for the South Pacific events are shown Figure 3. Note that the final 5 seconds of each time series is "wrapped around" to the beginning purposely to give a clearer picture of the first arrival. Because the latter part of the time series was zero padded before deconvolution, the rms amplitudes for the first 5 seconds can give some insight into the amount of noise present.

There is strong similarity between the stacked and the individual receiver function traces. The correlation coefficients ranged from 0.611 to 0.949, with an average of 0.805.

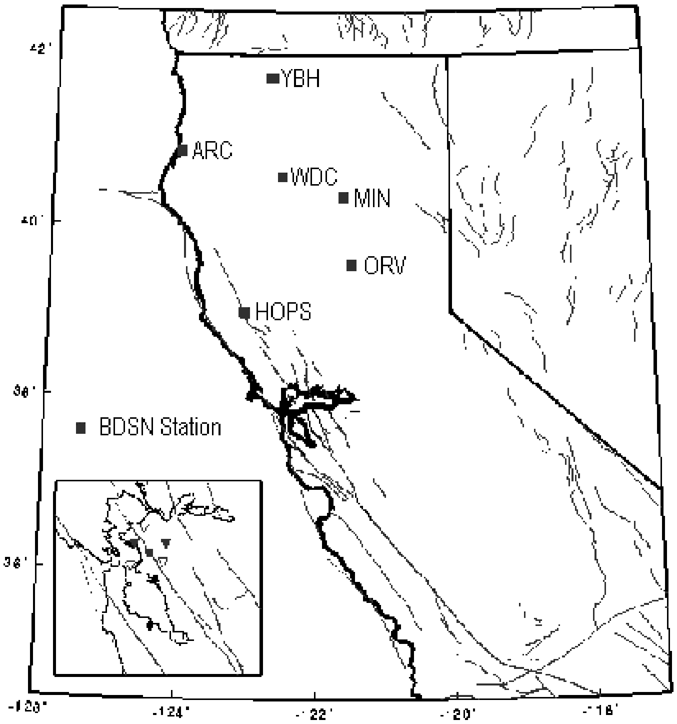

Figure 2. Berkeley Digital Seismic Network (BDSN) stations. YBH, ARC, WDC, MIN and HOPS were used in this study.

Station code	Station name	Latitude	Longitude	Elevation (m)
ARC	Arcata	40.877	-124.075	60
HOPS	Hopland	38.994	-123.072	299
MIN	Mineral	40.345	-121.605	1495
ORV	Oroville	39.556	-121.500	360
WDC	Whiskeytown	40.580	-122.540	300
YBH	Yreka	41.732	-122.710	1110

Table 1. Berkeley Digital Seismic Network (BDSN) broadband stations used in this study.

date	latitude	longitude	depth(km)	M_0	location
03/09/94	-18.039	-178.413	562.5	7.6	South Pacific
04/07/95	-15.199	-173.529	21.2	8.0	South Pacific
07/03/95	-29.211	-177.589	35.3	7.2	South Pacific
08/05/96	-20.690	-178.310	550.2	7.4	South Pacific
09/20/97	-28.683	-177.624	30.0	7.2	South Pacific
10/14/97	-22.101	-176.772	167.3	7.7	South Pacific
03/29/98	-17.576	-179.061	536.6	7.2	South Pacific

Table 2. Locations and magnitudes for the 7 events used in the inversion.

As a first approximation of Moho depth below each station, a simple inversion is performed assuming a constant crustal velocity of 6.5 km/s to find depths for the major amplitude peaks on the stacked receiver functions. On the receiver function for the station at Arcata two amplitude peaks are visible in the first 5 seconds, corresponding to depths of 21.9 km and 32.0 km, respectively. It is likely that the crust is thinnest in this region (Verdonck and Zandt, 1994; Benz et al., 1992), so the first amplitude peak is most likely caused by a P-S conversion at the Moho at 21 km depth. The receiver function determined from the station at Hopland shows amplitude peaks corresponding to 26.4 and 37.1 km depth, and, because, this is still in the Coast Ranges, 26.4 km is the most likely Moho depth. The receiver function for the station at Mineral has a long, flat amplitude peak that begins at 31.1 km and begins to recede at 46.6 km. Sustained positive amplitude on a receiver function is associated with a gradual increase in velocity, so it is possible that there is a slower transition to mantle velocities in this region. The receiver function determined for Oroville has significant amplitude peaks corresponding to 31.4 and 39.7 km. Located in the Sierra foothills, it is likely to overlie a fairly thick crust, so the choice is not as obvious as with the previous ones. The receiver function calculated for Whiskeytown has two obvious amplitude peaks which correspond to 34.2 and 48.0 km in depth. Lastly, the receiver function determined from the station at Yreka has major amplitude peaks which correspond to depths of 32.6 km and 41.4 km, although the peak at 41.4 km is the larger of the two, implying that the conversion at 41.4 km has the largest impedance contrast.

Following Ammon et Al. (1990) the approach that is used here is to model the receiver functions with many thin layers of fixed thickness. However, modeling with too many thin layers can produce unstable solutions. The fit may be quite good, but the model will have many alternating high and low velocity layers that may not be realistic. Because the problem is inherently nonunique it is desirable to minimize the number of degrees of freedom in order to find the simplest model that fits the data. To accomplish this, a minimum roughness constraint is added to the objective function, with the model roughness being calculated using an $\|\mathbf{L_2}\|$ norm:

$$X_r = \sum_{i=1}^{n} \left[\left(\alpha_{i+1} - \alpha_i \right)^2 \right]^{1/2} \tag{1}$$

where α_i represents the P wave velocity for each layer. The roughness parameter is then multiplied by a normalized weighting factor, which is found through trial and error. A value of 0.4 is used as a weighting factor for the minimum roughness constraint and 0.6 for the receiver function fit.

The inversion of the receiver functions was accomplished with the genetic algorithm (Goldberg, 1989). Genetic algorithms offer an attractive approach for many geophysical inverse problems in that they can explore the entire model space, are not dependent upon an initial estimate, require no derivatives, and are much more efficient than completely random search methods. A general study of this approach was necessary in order to determine how the control parameters of the method influence its performance when applied to realistic geophysical inverse problems. It was found that a particular choice of parameters consistently produced optimal results for a broad range of problem difficulties. At least for problems such as the inversion of receiver functions, the choice of a low mutation rate of about half the inverse of the population size was the most critical factor, with the crossover method and rate having a relatively minor affect upon performance. Tournament selection was found to be the most effective and robust selection method.

The inversion results are shown in Figures 3 and 4. Figure 3 shows the stacked receiver function and their fits. Figure 4 shows the models produced by the fits. The amplitude peak corresponding to the direct arrival on many of the South Pacific receiver functions cannot be fit adequately. Because the height of this amplitude peak is a function of the angle of incidence of the seismic wavefront, it is likely that dipping layers are producing an angle of incidence that is not as steep as the one that is used in the modeling.

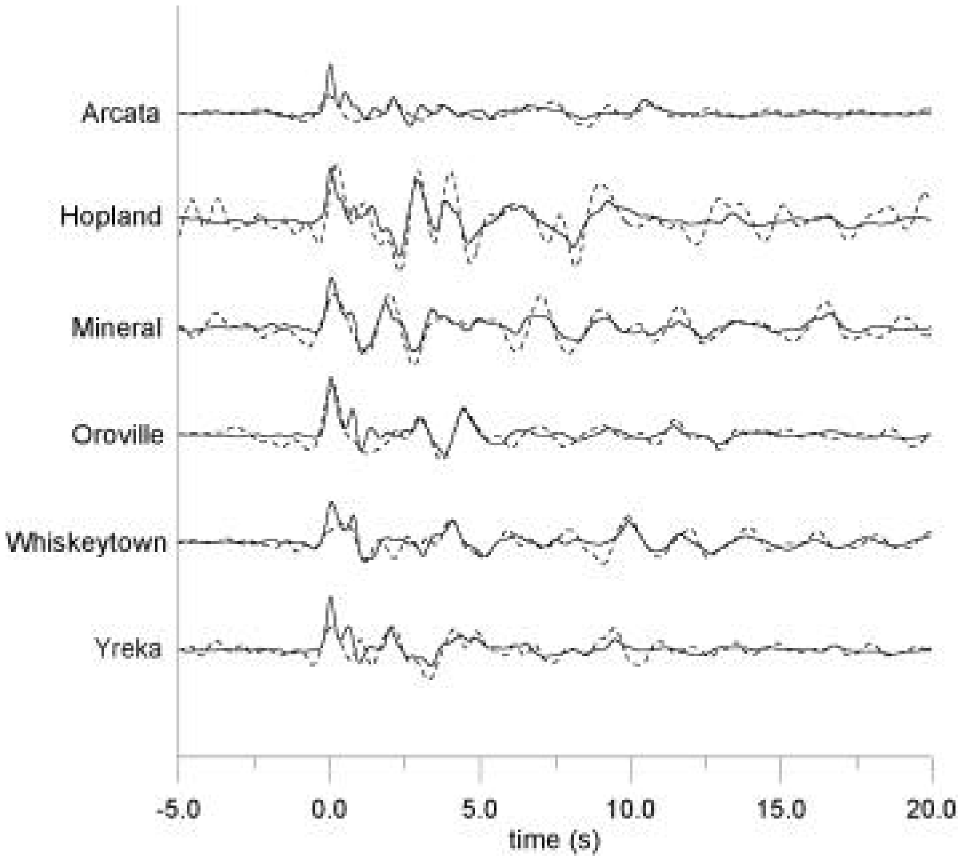

Figure 3. Stacked receiver functions for the 6 BDSN stations and their fits. Note that the last 5 seconds is wrapped around in order to observe the direct arrival more clearly.

Inversions results for the coastal station of Arcata imply a relatively flat velocity structure until 20 km depth, in which velocities jump to 7.4 km/s. Another smaller increase in velocity can be seen at 28 km depth. No consistent low velocity zone can be seen here. It would be interesting to look at receiver functions for a station at the same longitude as Arcata but south of the MTJ to see if there is a low velocity zone where Benz et al. (1992) suggest the existence of a slab window. Inversion results for the stations in the Southern Cascade Range are more interesting. The results derived for the station at Yreka (near the Oregon border) show a steep initial spike indicating a high velocity at about 4-6 km depth, followed by a consistent gradual rise to upper mantle values at about 36 km depth. Inversion results for the station at Whiskeytown show a relatively constant velocity profile down to about 46 km in depth, where the velocity jumps to nearly 8 km/s. Inversion results for the station at Mineral (near Mount Lassen) display a relatively constant velocity structure until 36 km depth, where there is a large increase to near mantle velocities. The results for the station at Oroville (in the Sierra Nevada foothills) are difficult to interpret as there is no obvious Moho conversion. Inversions for the Hopland station suggest a crustal thickness of about 32 km.

In Figure 5, the results from the direct interpretation of the receiver functions are plotted in two dimensions for the purpose of comparison with existing subduction models of the MTJ region. Estimated depths derived from amplitude peaks on the stacked South Pacific receiver functions, which are larger than 50% of the direct arrival peak and fall between 2.3 and 5.8 seconds (corresponding to roughly 20-50 km depth

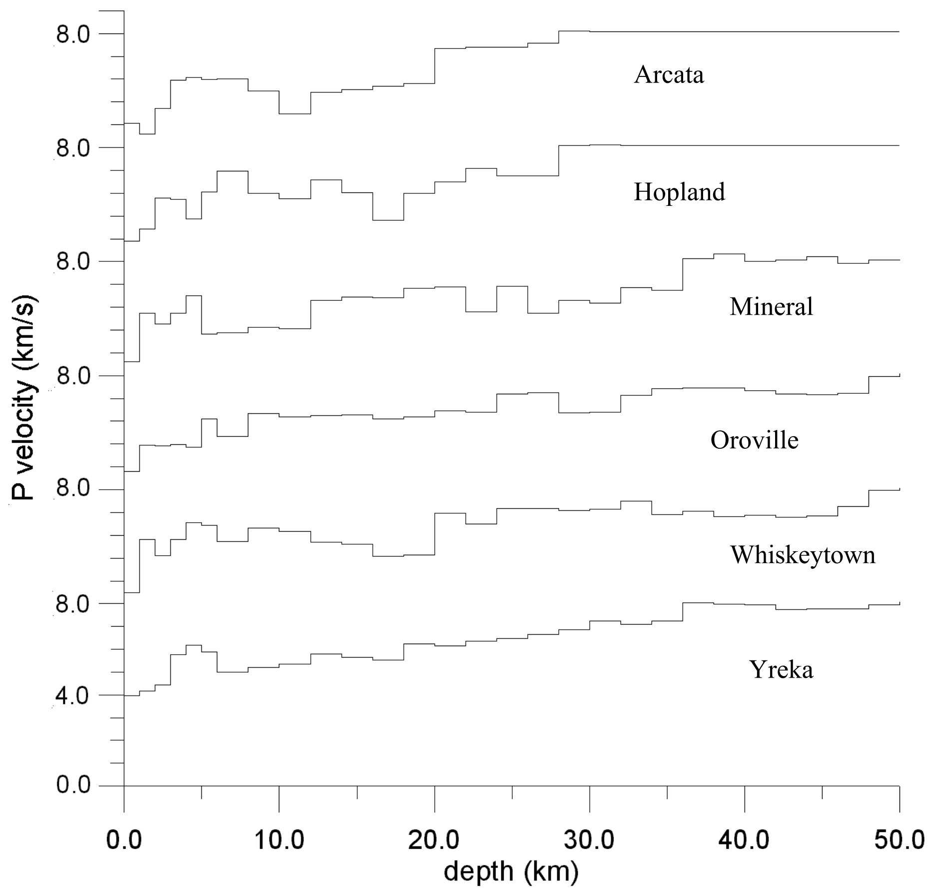

Figure 4. Models produced by the receiver function fits in figure 3. Each tick mark on the vertical axis corresponds to 1 km/s.

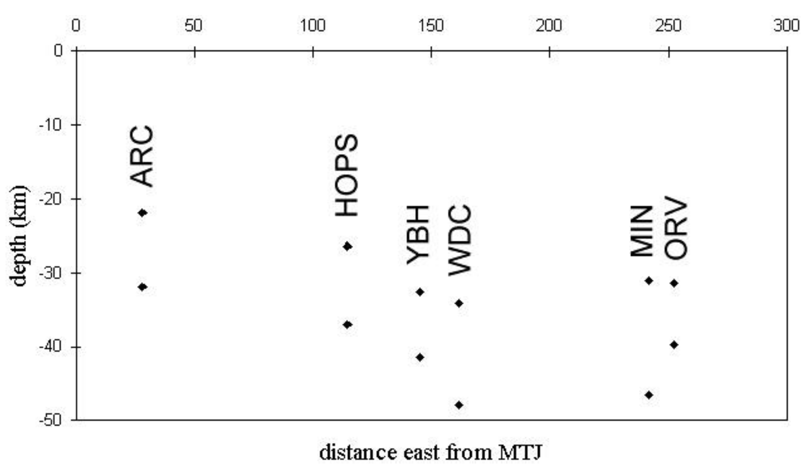

Figure 5. Receiver function conversions inverted for depth

if a constant velocity of 6.3 km/s is assumed for the region), are plotted as a function of one-dimensional distance from the MTJ. The results are consistent with the schematic in Figure 1 for the case where $V_1 < V_2 < V_3$. Assuming the lowest points correspond to conversions originating from the bottom of the Gorda

Plate, the dip on the Gorda Plate can be estimated. Between the stations ARC and HOPS the dip is approximately 3.5^{O}, between HOPS and YBH it is approximately 8.0^{O}, and between YBH and WDC approximately 22.3^{O}. This agrees closely with the estimated dip of the Benioff zone in the region between YBH and WDC but is considerably lower than that for the dip of the Benioff zone near the coast. The two higher points representing conversions for the stations Oroville and Mineral have approximately the same depth at 31 km. If these are Moho conversions, the lower points could be conversions from slab fragments as suggested by Benz et al. (1992). An alternative interpretation for the apparent thickening of the crust is simply the isostatic compensation for the Cascade Range. If this hypothesis is correct then the two lower points in Figure 5 for Oroville and Mineral may be more consistent with Moho depth and the two higher points could be the result of mid-crustal boundaries.

CONCLUSIONS AND RECOMMENDATIONS

Receiver functions are an effective means of obtaining velocity structures for any region that contains seismographic stations. The basic requirement of three-component data from a few teleseismic events is easily met in most cases.

The genetic algorithm can be used for the inversion of the receiver functions to obtain velocity models. With a proper choice of the control parameters, this proves to be an efficient method of exploring the entire range of possible velocity models.

Empirical receiver functions contaminated by noise and/or affected by dipping layers can lead to unrealistic or unstable models with extreme velocity variance. In this case, multiobjective optimization can be used to add a minimum roughness constraint to the objective function. Some amount of experimentation is necessary to find a suitable trade-off between data fit and model smoothness.

In addition to carrying out formal inversion procedures, direct interpretations of receiver functions can provide a great deal of information. Assuming a constant velocity in the crust and then calculating the depths which correspond to significant amplitude peaks on the receiver function can give a rough estimate of the depth and dip of the Moho and other discontinuities.

The receiver functions only provide vertical velocity profiles at the locations of the seismographic stations and it is necessary to use some form of interpolation to obtain models for the intervening regions. We are currently using regional gravity data to help constrain this interpolation.

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