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Detection of the low velocity layer atop the 410-km discontinuity beneath Northeast China with Slowness based CCP stacking

by

Xiaojiao Pang

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APPROVED, THESIS COMMITTEE

Fenglin Niu, Professor, Earth Science

Alan Levander, Professor, Earth Science

Cin-Fu A. Lee, Professor, Earth Science

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ABSTRACT

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The structure and tectonics of Northeast China are predominantly affected by the interactions of the Pacific plate and the Eurasia plate. The mantle transition zone (MTZ) structures are also influenced due to this interaction. The importance of the MTZ in advancing understanding of mantle dynamics is highlighted by the Transition Zone Water Filter (TZWF) model, which predicts the existence of a partial-melt layer atop ‘410’, hereafter referred to as 410-LVL (Low Velocity Layer). In recent years, efforts to investigate the 410-LVL are accelerating. Regardless of the veracity of the TZWF model, it is clear that a more complex role for the MTZ in thermochemical mantle convection is emerging and that higher resolution seismic mapping of lateral variations in mantle layering will provide valuable constraints on the thermal and chemical processes active in the MTZ. The presence of a global layer of partial melt above the ‘410’ discontinuity would modify material circulation in the Earth’s mantle and may help to reconcile geophysical and geochemical observations. We collect the data in Northeast China mainly from NECESSArray and CEArray. By first screening the raw data and then generating the receiver functions from the selected data, we are able to use the common conversion point (CCP) method to do the stacking of the receiver functions. After the stacking, the common
features will emerge. However, we are not clear whether some of the features are real structures or processing artifacts. We introduce the slowness based CCP stacking method to further confirm the existence of 410-LVL. With additional support from the statistical analysis of the results, we are able to finalize the detections of the 410-LVL. The LVL is not related to a particular type of geodynamical environment atop the ‘410’: it is found globally with various geological settings. The NE China area is predominantly affected by the subduction of the Pacific plate under the Eurasia plate. The stagnant slab has the ability to add a large amount of subducted fluid into the mantle. Slab dehydration creates the 410-LVL, along with the potential for subsequent triggering of wet mantle upwelling.
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Chapter 1

Introduction

The mantle is the second layer of the Earth, and it plays an important role in the dynamic system of the Earth. It is divided into the upper mantle and the lower mantle by the mantle transition zone (MTZ) defined within the 410-km and the 660-km seismic discontinuities. These two discontinuities are generally attributed to phase transitions in the olivine-dominated mantle assemblage (Ringwood, 1975). Lateral undulations of the two discontinuities, subsequently the MTZ thickness, were speculated to be thermally sensitive (Helffrich, 2000). However, recent studies have shown that both volatiles and chemical compositions can also affect seismic structures within and around the MTZ.

With the increasing coverage of seismic stations over the last few decades, low-velocity layers are frequently observed right above the 410-km discontinuity (hereafter referred to as 410-LVL) and below the 660-km discontinuity using
various methods (Schmandt et al., 2011; Tauzin et al., 2010) (Figure 1). For example, the 410-LVL is detected at Arabia (Vinnik et al., 2003), eastern Asia (Revenaugh and Sipkin, 1994), eastern Australia (Courtier and Revenaugh, 2007), eastern U.S. (Courtier and Revenaugh, 2006), northern Mexico, northwestern Canada (Bostock, 1998; Schaeffer and Bostock, 2010), Siberia (Vinnik and Farra, 2002), and western U.S. (Song et al., 2004; Fee and Dueker, 2004; Jasbinsek and Dueker, 2007; Vinnik et al., 2010; Jasbinsek et al., 2010). In general, the 410-LVL is found globally in various geological settings. The robustness of those observations is also questionable. Furthermore, the thermal interpretation of the low-velocity layers appears to be difficult as more and more modelling results show that thicker anomalies are needed to reconcile the arrival time and amplitude of the P-to-S conversion phases happening at the LVL depths (Schmerr and Garnero, 2007). They were usually interpreted by partial melting, indicative of the presence of water within and near MTZ. Before conducting the interpretation, we need better imaging techniques to map the geophysical behavior of the MTZ.

Northeast (NE) China is a tectonically active region lying more than 1000 km west of the Japan Trench. It consists of the NE China Plain with the Songliao Basin at its center, and the Changbai volcano, the Great Xing’an Range, and the Sino-Korean Craton to the east, the west, and the south, respectively. Located in the NE Asia, NE China is predominantly affected by the topography, seismic and volcanic activities, intensive deformations of the lithosphere, and many other intriguing geological and geophysical features. In addition, recent studies imply that the zone beneath northeast China is remarkably hydrous (Kuritani et al., 2011). This very complex
geological and tectonic setting provides us a unique laboratory for studying the interaction of slab with MTZ, especially the possible existence of the 410-LVL, which can further our understanding of mantle dynamics and material circulation.

In this study, we collect the teleseismic data in NE China mainly recorded by NECESSArray and CEArray stations. After initial quality control of the raw data, we calculate the receiver functions for the common conversion point (CCP) method that does receiver function stacking. After the stacking, we observe the common features in the CCP stacking profiles. In order to get rid of the reverberation phases but maintain conversion phases in CCP stacking results, we introduce the slowness based CCP stacking method, which significantly improves the resolution of the discontinuity structures. In the results, we see the 410-km discontinuity clearly marked by the common positive P-to-S conversion phases occurring at approximately 410 km deep. Another feature that cannot be ignored is the negative amplitudes atop the 410-km discontinuity, indicating a possible low velocity layer.

In this project, my objective is to get robust detections of the 410-LVL beneath NE China, and then propose a convincing model to explain the detections. I hope to make contribution to the understanding of mantle convection and material circulation in the NE China area.
Figure 1. From Tauzin et al. [2010]. Global map showing previous observations of a low-velocity layer atop the 410-km discontinuity. Outlined red stars are data from P-to-S conversions (Ps) at individual stations. Red stars are data from S-to-P conversions (Sp) at individual stations. Observations from ScS reverberations are indicated in green. Observations from a joint study of Ps ans S-wave triplications are indicated in blue. Ps and Sp array observations are indicated in red.
The description of the methods is composed of three parts; first, what is receiver function (RF); second, what is the common conversion point (CCP) stacking technique; last, what is the slowness based CCP stacking method designed to remove the reverberations in the stacking results.

2.1. Receiver function technique

The receiver function technique is a classic way to model the subsurface structures with teleseismic waves. A teleseismic P-wave will generate P to S conversions and reverberations at discontinuities beneath the seismic stations. The travel time difference between those phases will reveal information about the distance to the boundary. With seismograms recorded at three-component seismic sensors from teleseismic earthquakes (within the epicentral distance range of 30° to
90°), we will be able to extract the information of the earth structures sampled by the ray paths propagating through the earth. In fact, receiver function methods are sensitive to discontinuities in seismic studies. Generally speaking, the recorded seismograms are composed of the source information and propagation media information. If we could remove the source information, the remaining will be purely about the propagation media property. The problem of removing source information from the recorded seismograms is solved by deconvolution (Figure 2a). (Vinnik, 1977; Niu and Kawakatsu, 1998; Niu et al., 2005). Receiver function has become a standard and popular technique to constrain crustal and upper mantle velocity discontinuities under a seismic station.

In the implementation, we first rotate the two horizontal components of the seismograms to the P and SV components. Then we apply a time window to the time series of the estimated P arrival part, choosing the appropriate source signal. Finally we employ the “water-level” deconvolution technique (Clayton and Wiggins, 1976) to generate receiver functions. The equation for “water-level” deconvolution is as follows:

$$E_{RF}(\omega) = \frac{V(\omega)P^*(\omega)}{\max\left\{P(\omega)P^*(\omega), k|\max(\omega_0)|^2\right\}} e^{-\left(\frac{\omega}{2a}\right)^2}$$ (1)

Here $\kappa$ defines “water level” and $a$ defines the corner frequency of the Gaussian low pass filter. The water level $\kappa = 0.01$ is selected. We use $a = 0.5$ in this study, equivalent to a corner frequency of 0.2 Hz. $P(\omega)$ and $V(\omega)$ are the frequency
spectra of the P and SV components. We use a 100 s time window (5 s and 95 s before and after the P wave arrival) to compute the source spectrum of each earthquake. We further screen the receiver functions to remove noisy data.

2.2. Common Conversion Point stacking

The idea of common conversion point (CCP) originates from the routine data processing technique, the common middle point (CMP) stacking in reflection seismology. Both of them are designed to back-project the energy received at the surface to the subsurface positions where it might be from. The CMP technique was modified to suit the global seismology scenario, getting the common conversion point (CCP) stacking technique, which helps to improve the signal-to-noise ratio for receiver function imaging (Dueker and Sheehan, 1997; Li et al., 1998; Owens et al., 2000; Zhu, 2000; Ai et al., 2003; Gilbert et al., 2003; Niu et al., 2005). This is also one of the most popular methods in global seismic imaging. Nowadays, the availability of a large number of broadband high-quality seismic data provides the opportunity to get advanced and more reliable image of deep structures with teleseismic data.

For each receiver function, we compute the theoretical P arrival time with the ray-tracing technique first. Then conversion points at each depth will be calculated. For each depth \( d \), we keep the geographic location of the conversion point. Meanwhile, ray-tracing of both the P and S phase is conducted using the 1D IASP91 velocity model (Kennett and Engdahl, 1991). Then we have the location of
the conversion points and the travel time difference between the converted phase Pds and the direct P phase. After processing all the receiver functions, we gather the receiver functions to improve the signal to noise ratio. We divide the study area into meshed grids. For each grid, we apply a circular cap with a radius of larger degree for gathering the receiver functions with conversion points falling into the same cap. There are significant overlaps among the caps. This serves to low-pass filter the topographic relief with a corner wavelength roughly equivalent to the size of the caps. (Wang and Niu, 2011). Instead of linear stacking the receiver function amplitudes centered on the arrival times of Pds, we apply the Nth-root stacking technique (Muirhead, 1968), which is capable of amplifying the coherence of different traces. For the $i^{th}$ cap, let $r_k(t)$ represents the $k^{th}$ receiver function gathered in the cap, and $t_{dk}$ is the Pds arrival time for a discontinuity with a depth of $d$, an Nth-root stack, $R(d)$, is given by

$$R_i(d) = y_i(d)|y_i(d)|^{N-1}$$  \hspace{1cm} (2)

Where

$$y_i(d) = \frac{1}{K} \sum_{k=1}^{n} w_k \text{sign}[r_k(t_{de})] r_k(t_{de})^{1/N}$$  \hspace{1cm} (3)

Here $K$ is the total number of receiver functions gathered at the $i_{th}$ cap. $w_k$ is a Gaussian weight function:
\[ w_k = \frac{\exp\{-x_k^2 / a^2\}}{\sum_{n=1}^{N} \exp\{-x_n^2 / a^2\}} \]

(4)

Here \( x_k \) is the distance between the cap center and the conversion point of the \( k \)th-event. The Gaussian width parameter, \( a \), was set to be the same as the cap radius. We chose \( N=2 \) to reduce the uncorrelated noise. Usually we vary \( d \) from 200 km to 1000 km with 1 km increment.

It's important to select the appropriate CCP binning according to the density of the data array, and to do the subsequent stacking, which has been proved to be able to significantly improve both the signal-to-noise ratio and thus the spatial resolution of the results.

### 2.3. Slowness based CCP stacking of the data

In the above description, we already build a work flow using the P-to-S conversion database to investigate the existence and characteristic of the 410-LVL. The CCP method is about the back-projection of recorded energy at the surface to subsurface positions where it comes from. Here we assume that the stacked receiver functions only contain P-to-S conversion phases. In fact, compared to other phases, the Ps conversion phase could avoid the interference with other major seismic phases. However, multiple reverberations will still appear in the 200-400km depth range leading to phases with large amplitudes in the CCP stacking results, which will contaminate the CCP results (Figure 2b). Careful analysis of those phases is needed to eliminate the reverberation phases and
to maintain the desired P-to-S conversions. Here, we introduce the slowness analysis of the database in each grid.

A seismogram with a specific source and receiver is composed of several phases such as the direct P phase, P-to-S conversion phases, other reverberation phases, and so on. Figure 2c describes the ray path geometry of three phases with incident P wave: direct P phase, P-to-S conversion phase, and P-to-S reverberation phase. It is clear that although these phases share similar incident P wave paths before conversion, there are still slight differences between the ray parameters of these phases. The ray parameter of the reverberation phase is larger than that of direct P phase, and direct P phase ray parameter is larger than that of P-to-S conversion phase. That is to say, the P-to-S conversion phase, and reverberation phase have a negative and positive relative ray parameter with respect to the direct P phase, correspondingly. At the same time, ray parameter also relates to the moveout of the arrival time. When we align the seismograms with the P phase, along with the increase in epicentral distance, a decrease of P-to-S conversion arrival and an increase of reverberation arrival are expected, that is, a negative and positive moveout respectively. (Chen and Niu, 2013). When doing the slowness analysis, by stacking seismograms along with different ray parameters, we could expect energy concentrations at corresponding negative and positive ray parameters for conversion phases and reverberation phases. Therefore, we could confirm whether the phase is conversion or reverberation and further determine the true discontinuity structures.
In our study, since we are interested in the conversion phases, we could design the weights to highlight the conversion phases while diminish or even eliminate the reverberation phases. For each CCP grid profile, we will do the slowness analysis for all the depths. For each depth, the workflow is designed in this way: first, search the slowness analysis result along with the relative arrival time to get the peak position. This position indicated by the ray parameter is called the observed slowness. Next we calculate the theoretical slowness assuming conversion happens at this depth. This slowness is called calculated slowness. The weight at each depth is designed in equation (5), in which \( p_c \), \( p_o \) represent the calculated and observed slowness respectively. The closer \( p_c \) and \( p_o \) are, the higher the likelihood that conversion instead of reverberation happens at that depth. It is worth noting that at a shallower depth, even though \( p_o \) may be positive, the weight can also be relatively large since \( p_c \) is a rather small negative number. Thus we also apply a factor depending on \( p_c \) value, larger weight will be applied with the increase of \( p_c \). In the end, the weights are applied to the regular CCP stacking results with the intention to diminish or even eliminate the reverberation phases.

\[
w_d = \exp \left( - \left( \frac{p_c - p_o}{0.05} \right)^2 \right) \cdot \left| \frac{p_c}{0.3} \right|
\]

We are aware that although energy concentration is observed at position with negative slowness, there is still possibility for the phase to be processing artifacts, for example, sidelobes. Therefore, we conduct the statistical analysis of the interested phases. Take the phase above the 410-km discontinuity for example, we
generate receiver functions with different corner frequencies, and then apply the CCP method with those receiver functions, getting two sets of results. By comparing the phase locations in these two CCP results, we can see whether they will change along with different frequencies. Real phases should appear at the same location in different CCP results. This provides a way to further test the robustness of the 410-LVL detection.

(a)

(b)
Figure 2. Receiver Function schematic diagram. (a) *(from Ammon, 1991)* Vertical and radial response and the receiver function calculated for a single layer above a half-space. The amplitude relationship between the synthetic response and the receiver function is indicated to the left of the traces; (b) Scenario where reverberation phase and conversion phase arriving at the same time in receiver function; (c) Ray path diagram.
Chapter 3

Data

Besides the CEA array (China Digital Seismic Network under the China Earthquake Administration) data covering all of China, we also combine the newly collected data from the NorthEast China Extended Seismic Array (NECESSArray). The NECESSArray project is primarily focused on the fate of the subducted Pacific plate. The experiment lasted about two years from September 2009 to August 2011, involving collaboration with scientists from Peking University, the Earthquake Research Institute (ERI) of Tokyo University and the Japan Agency for Marine-Earth Science and Technology, providing high-quality data collected in the NE China area. Our research area covers 115E–135E and 40N–49N, roughly ~2000 km and ~900 km in the EW and NS directions, respectively (Figure 3). We visually check all the 44959 teleseismic data (within the epicentral distance range of 30° to 90°) from earthquakes with magnitude larger than 5.0, which are recorded by the
PASSCAL/ERI stations between September 2009 and August 2011 and by the CEA stations between July 2007 and October 2010. These earthquakes provide a good coverage in both distance and azimuth (Figure 4). Fortunate for us, this is one of the areas with best data coverage globally.

**Figure 3.** Map showing topography, major faults, and tectonic units of NE China. The purple lines outline major basins in the area. The black solid lines and the dotted yellow lines represent the large strike-slip faults and major suture zones, respectively. Blue solid squares and black solid triangles represent the temporary and permanent broadband stations of the NECESSArray, respectively. Red volcanic symbols show the three magmatic centers in the area, Wudalianchi, Jingpohu, and Changbaishan, among which Changbaishan is the largest active magmatic center in China. Solid circles indicate major cities in the area. The bottom-right inset shows the motion of the Pacific plate relative to the Eurasia plate.
Figure 4. Distribution of the earthquakes (red stars) used in this study. The blue triangles indicate the center of the seismic array.
Chapter 4

Results

As described above, we use the CCP method to stack the receiver functions sharing the same conversion caps.

Take one grid point (125°E, 42.6°N) for example: Figure 5(a) shows the regular CCP stacking result of the grid. Figure 5(b) is the slowness analysis result at depth 672km. We could see the clear energy concentration of the six major peaks marked in Figure 5(a). By comparing the observed slowness with the calculated slowness, we then design the weights according to equation (5). Figure 5(c) is the resulting slowness based CCP stacking profile. We can see that major conversions are maintained and the reverberations appearing between 200km and 300km are processed with very small weights.

Figure 6(a), (b), (c), (d), (e), (f), (g), (h) are the regular CCP stacking results along with latitude 40°N, 41°N, 42°N, 43°N, 44°N, 45°N, 46°N, 47°N respectively.
After applying the designed weights, we get Figure 7(a), (b), (c), (d), (e), (f), (g), (h) correspondingly.

It is worth noting that there are clear negative phases just below the 410-km discontinuities. To further test the robustness of the phases around the 410-km discontinuity, I generate the receiver functions with different a value in equation (1) (here \(a=0.5\) and \(a=1.5\) are used), then CCP results with those receiver functions are acquired respectively. If those phases are robust, they should exist at the same locations in different CCP results. Statistical analysis of those phase location discrepancies is necessary here. I manually pick the phases above, at and under the 410-km discontinuity, above and at the 660-km discontinuity in both results, and compare the five differences. Figure 8, 9, 10, 11, 12 are the histograms of those phase location discrepancies respectively.

For each result, we also calculate the mean value and variance. The closer to zero the mean value is, the more likely that the phase indicates real structures. The smaller the variance is, the more robust the phase location is. With the statistical analysis, we can confidently say that the phase atop the 410-km discontinuity indicates real structures, while the phase below the 410-km discontinuity and above the 660-km discontinuity are processing artifacts (for example, side-lobes).
Figure 5. (a) Regular CCP stacking result for grid point (125°E, 42.6°N). X axis is depth (km) and Y axis is the stacked amplitude; (b) Slowness analysis result; (c) Slowness based CCP stacking results for grid point (125°E, 42.6°N). A, B, C, D, E, F are the peaks of the six major phases in CCP result.
Figure 6. Regular CCP stacking profiles along 40°N, 41°N, 42°N, 43°N, 44°N, 45°N, 46°N, 47°N.

We also get the 410-km discontinuity and the 660-km discontinuity topography from the slowness based CCP results. The results are plotted in Figure 13. From the improved results, we use the standard that the amplitude ratio of the converted phases occurring atop the 410 discontinuity over the maximum of amplitudes occurring at the 410-km and the 660-km discontinuity should be large enough. This confirms that the 410-LVL is more likely to be a true signal rather than
a processing artifact. The resulting detections of the 410-LVL are shown in Figure 13 with black crosses.

**Figure 7.** Slowness based CCP stacking profiles along 40°N, 41°N, 42°N, 43°N, 44°N, 45°N, 46°N, 47°N.
Figure 8. Histogram of the phase (above the 410-km discontinuity) location discrepancy.

Figure 9. Histogram of the phase (at the 410-km discontinuity) location discrepancy.
Figure 10. Histogram of the phase (below the 410-km discontinuity) location discrepancy.

Figure 11. Histogram of the phase (above the 660-km discontinuity) location discrepancy.
**Figure 12.** Histogram of the phase (at the 660-km discontinuity) location discrepancy.
**Figure 13.** Map view of low velocity layer distribution in the research area. The detections are indicated with black crosses. The backgrounds of the figure are 410-km discontinuity topography, 660-km discontinuity topography, and transition zone thickness respectively.
Chapter 5

Discussion

From Figure 6, Figure 7 and Figure 8, we can judge that the negative signal atop 410-km discontinuity is not likely a side-lobe of the P410s waveform because of lacking a symmetric side-lobe with similar amplitude underneath the 410-km discontinuity. Besides, the negative signal is not observed at all the grids even with clear P410s phases. Also, the distance between the negative signal and the 410-km discontinuity varies with the station locations but remains the same at results from different-frequency data. By the slowness analysis, we have reasons to trust the reliability of our detection results.

The comparison of Figure 6 and Figure 7 shows significant improvement of our method. We can see that the 200km-300km depth structures are carefully sorted. The reverberation phases are muted to a large extent, leaving those potential conversion structures. In addition, we get better resolution than the regular CCP
method for the whole area with the slowness based CCP method. Not only the two major discontinuities, but also the 410-LVL stand out. For the other phases to be determined, we also have them systematically processed, making the results easier to analyze.

From Figure 13, especially from the 660-km discontinuity topography and the transition zone thickness structures, we could see that slab stagnation might not be occurring in the southern part of NE China. In addition, we found that, most of the detections are concentrated at the southern part of our research area, the place where Changbai volcano is located. It’s very meaningful to get a convincing model related to the MTZ structures, committed to better understanding of material circulations in the NE China area.

It has been widely accepted that the 410-LVL is due to the partial melting of the upper mantle. When it comes to the reason for the partial melting, there have been different opinions. Recently, some atypical dehydration mechanisms are proposed. For example, Faccenna et al. (2010) proposed the possible decompression melting induced by slab return flow that rises the front and side edges of the subduction slab. Inspired by this hypothesis, Tang, et al. (Tang, Niu, et al., 2014) conducted the seismic tomographic method near Changbai Volcano area, they proposed that the subduction-induced upwelling process produces decompression melting that feeds the Changbaishan volcanoes. This might also apply to other back-arc volcanism observed at other subduction zones. In our results, we also observed the 410-LVL in Changbaishan area, which supports this
hypothesis. Since the 410-LVL occurrence is not related to a particular geodynamical environment but is controlled by local conditions near the 410-km discontinuity, in Northeast China, the leading characteristic is the subduction, we might at least be able to try finding the connection between the 410-LVL and the subduction features.

From the geochemical observation and analyses, the mantle transition zone beneath northeast China is remarkably hydrous (Kuritani et al., 2011). We are aware that the NE China area is predominantly affected by the subduction of the Pacific plate under the Eurasia plate. The subducted slab of the Pacific plate extends horizontally over a distance of 800 to 1,000 km in the MTZ at the 660-km discontinuity. Such a stagnant slab has the ability to add a large amount of subducted fluid into the mantle, with the potential for subsequent triggering of wet mantle upwelling (Wang et al., 2015). With Kuritani et al.'s model (2011) demonstrating that the mantle transition zone can remain as a stable water reservoir in Earth's interior for timescales of more than a billion years, Wang et al. (2015) proposed a model (Figure 14) that MTZ is hydrated by the subducted slab, which further leads to the resulting wet upwelling. This model shows good consistency with our observations. The Pacific slab was subducted from the southeast. Thus the extent of MTZ hydration is gradually reduced along with the process when the slab moves in the northwest direction. In Figure 13, we see that the major detections of the 410-LVL follow the same trend.
Figure 14. From Wang et al. [2015]. Effects of slab stagnation and water cycling on the upper mantle thermochemical state. Water cycling refers to wet upwelling, upward percolation and refertilization. This model is mainly based on the strong spatial correlation of geochemical features with distance of eruptive lavas relative to the edge of the stagnant slab. This is based on water partitioning in the Earth’s mantle, behavior of slab-triggered wet upwelling and upward percolation, hydrous mantle melting, the mantle wedge model, and upwelling from the hydrated mantle transition zone.

In the results, we find that the detections of 410-LVL show clear patterns with complexity. A variety of mechanisms might be involved to produce the partial melting atop the 410-km discontinuity. With the reliable results on the 410-LVL structures and convincing interpretations of my results, I hope to make some contributions to the understanding of the mantle convection and material circulation in the NE China area.
Chapter 6

Summary

The NE China area is predominantly affected by the subduction of the Pacific plate under the Eurasia plate. This provides an ideal laboratory for the study of interaction between slab and mantle transition zone, especially the possible existence of the 410-LVL. We collect the data in Northeast China mainly from NECESSArray and CEAarray. By first screening the raw data and then generating the receiver functions from the selected data, we are able to use the common conversion point (CCP) method to do the stacking of the receiver functions calculated for NE China. Concurrently, the slowness based CCP stacking method is developed and conducted. Designed to eliminate reverberations while maintaining conversions, the slowness based CCP stacking method shows significantly improved resolution of 410-LVL than the regular CCP stacking method. The suspicious reverberation phases within 200-300km depth range are eliminated to a large
extent while the 410-LVL, the 410-km discontinuity and the 660-km discontinuity stand out in the results. By statistical analysis of the phase location differences in CCP results from receiver functions generated with different corner frequencies, the robustness of the 410-LVL detections is strengthened. We also get the 410-km, 660-km discontinuity and the mantle transition zone thickness, from which we find that the mantle transition zone is broadly deeper in the northeastern part of the research area.

The 410-LVL detections are concentrated in the southeastern part of the study area, where the Changbai Volcano complex and major parts of the Songliao Basin are located. Parallel to the Pacific plate motion direction, which is due NW, the 410-LVL is detected in about 42 percent of the study area, and the observations gradually decrease from southeast to northwest. The 410-LVL detections show clear patterns with complexity, therefore a variety of mechanisms might be involved for the generation of partial melting atop the 410-km discontinuity. If we assume that 410-LVL is caused by water induced partial melting, this observation might suggest the decreasing extent of MTZ hydration from the subduction slab when moving from southeast to northwest.
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