Measurement of Rayleigh wave ellipticity and its application to the joint inversion of high-resolution S wave velocity structure beneath northeast China

Guoliang Li1,2, Haichao Chen1, Fenglin Niu1,3, Zhen Guo2,4, Yingjie Yang2, and Jun Xie2

1State Key Laboratory of Petroleum Resources and Prospecting, and Unconventional Natural Gas Institute, China University of Petroleum, Beijing, China, 2Australian Research Council Centre of Excellence for Core to Crust Fluid Systems and GEMOC, and Department Earth and Planetary Science, Macquarie University, North Ryde, New South Wales, Australia, 3Department of Earth Science, Rice University, Houston, Texas, USA, 4Institute of Theoretical and Applied Geophysics, Peking University, Beijing, China

Abstract We present a new 3-D S wave velocity model of the northeast (NE) China from the joint inversion of the Rayleigh wave ellipticity and phase velocity at 8–40 s periods. Rayleigh wave ellipticity, or Rayleigh wave Z/H (vertical to horizontal) amplitude ratio, is extracted from both earthquake (10–40 s) and ambient noise data (8–25 s) recorded by the NorthEast China Extended Seismic Array with 127 stations. The estimated Z/H ratios from earthquake and ambient noise data show good consistency within the overlapped periods. The observed Z/H ratio shows a good spatial correlation with surface geology and is systematically low within the basins. We jointly invert the measured Z/H ratio and phase velocity dispersion data to obtain a refined 3-D S wave velocity model beneath the NE China. At shallow depth, the 3-D model is featured by strong low-velocity anomalies that are spatially well correlated with the Songliao, Sanjiang, and Erlian basins. The low-velocity anomaly beneath the Songliao basin extends to ~2–3 km deep in the south and ~5–6 km in the north. At lower crustal depths, we find a significant low-velocity anomaly beneath the Great Xing’an range that extends to the upper mantle in the south. Overall, the deep structures of the 3-D model are consistent with previous models, but the shallow structures show a much better spatial correlation with tectonic terranes. The difference in sedimentary structure between the southern and northern Songliao basin is likely caused by a mantle upwelling associated with the Pacific subduction.

1. Introduction

Although Rayleigh wave dispersion data have been extensively used to study the lithosphere and upper mantle velocity structure [e.g., Shapiro et al., 2005; Yang et al., 2007], it is widely accepted that the relative long-period Rayleigh waves (>8 s) extracted from either earthquakes or ambient noise have very limited resolution on shallow structures. On the other hand, knowledge on shallow velocity structure is of great importance for understanding surface geology [Lin et al., 2012], estimating strong ground motions, as well as better constraining deeper structures with surface data [Waldhauser et al., 2002; Bozdağ and Trampert, 2008; Langston, 2011]. Previous studies have shown that Rayleigh wave ellipticity or Z/H ratio is more sensitive to shallow structure than phase velocity dispersion data [e.g., Boore and Toksöz, 1969], allowing us to better constrain the near-surface shear velocity structure using Z/H ratio.

Although the theory of Rayleigh wave ellipticity was well established almost half century ago, its application to study the earth structure seems to fall behind, largely due to lack of high-quality multicomponent seismic data in early days and the difficulty in extracting accurate Z/H ratio from real data. Boore and Toksöz [1969] measure the Z/H ratios in frequency domain using earthquake Rayleigh wave data and find that the observed Z/H ratios are highly scattered. Recently, studies on robust extraction of Z/H ratio and its application to structural inversion [e.g., Tanimoto and Alvizuri, 2006; Ferreira and Woodhouse, 2007; Yano et al., 2009; Lin et al., 2012; Chang et al., 2014; Lin and Schmandt, 2014; Lin et al., 2014] have come under renewed interest because of the rapid increase of high-quality three-component broadband waveform data. Tanimoto and Rivera [2008] propose a cross-correlation-based technique to measure the Z/H ratio in time domain, which they claim to have sufficient accuracy for structural inversion. Lin et al. [2014] find that short-period Rayleigh wave ellipicities can be robustly extracted from ambient noise cross correlations and construct Z/H ratio maps of western U.S. at periods of 8–24 s, which exhibits a good correlation with surface geology.
Northeast (NE) China is a geological complex area consisting of basins and mountain ranges (Figure 1), and their formations are thought to be partly associated with the Pacific subduction. Recently, a large-scale broadband seismic array, the NECESSArray (NorthEast China Extended Seismic Array), was installed in the area by an international team to study deep subduction and lithosphere structure [Tang et al., 2014]. Using seismic data from the experiment, Tao et al. [2014] find that teleseismic recordings at stations within the basins are very complicated because of sediment reverberations, making it difficult to constrain the crustal and mantle structures beneath the stations. Guo et al. [2015] jointly invert receiver function and Rayleigh wave data for a 3-D S wave model of NE China and find that the shallow structure (<5 km) is poorly constrained due to the limited resolution of surface wave dispersion data.

In this study, we present a new 3-D S wave velocity model of NE China derived from joint inversion of Rayleigh wave ellipticity and phase velocities at 8–40 s periods. We extract Rayleigh wave ellipticities using both earthquake and ambient noise data from the NECESSArray, with the short- to intermediate-period measurements from earthquakes and short periods from ambient noise cross-correlation data. Combining the measured Z/H ratios and the phase velocity data, we jointly invert them for a 3-D S wave velocity model beneath NE China. Our 3-D model exhibits strong low-velocity anomalies at shallow depth with its lateral distribution being correlated very well with the geographic locations of the basins in the area, suggesting that the shallow structures are well constrained by the joint inversion.

2. The NECESSArray Data

The NECESSArray is a temporary broadband array deployed between September 2009 and August 2011 by an international collaborative project. It consists of 127 temporary broadband stations with averaged station spacing of approximately 80 km (Figure 1) and covers most part of NE China. The Songliao basin, about 750 km long and 330–370 km wide, is located at the center of the NE China. It is surrounded by the Great Xing’An range to the west, the Changbai Mountain to the southeast, the Zhangguangcai range to the east, and Lesser Xing’An range to the north (Figure 1). In addition to the Songliao basin, there are other three basins in NE China, the Hailar basin in the northwest, the Erlian basin in the southwest, and the Sanjiang basin in the northeast (Figure 1).
2.1. Ambient Noise Data

Our data processing procedures for the daily continuous ambient noise data are generally adapted from Lin et al. [2014], which are summarized as below. For each seismogram, we first remove the instrument response after subtracting the mean and linear trend and decimate the data to one sample per second [Bensen et al., 2007]. An antialiasing low-pass filter is applied to the data prior to the down sampling. Following Lin et al. [2014], we apply temporal normalization and spectral whitening to all the three components recorded at each station. After the above preprocessing, we finally calculate nine noise cross-correlation functions (NCFs), $Z-Z$, $Z-N$, $Z-E$, $N-Z$, $N-N$, $N-E$, $E-Z$, $E-N$, and $E-E$, for all possible station pairs. Here the first and second letters refer to the virtual source and regular receiver.

![Figure 2](image)

Figure 2. (a) Configuration of bearings of the raypath at the virtual source (azimuth) and the receiver (back azimuth). (b) Schematic diagrams showing Rayleigh wave signals recorded in the $Z$ and $R$ components by a station pair, station 1 and station 2. (c) Schematic diagrams showing the four cross correlations of $ZZ$, $ZR$, $RZ$, and $RR$ where station 1 is treated as a virtual source and station 2 is regular receiver.
source and receiver stations, respectively. A rotation matrix is used to rotate the nine NCFs to radial (R) and transverse (T) components. The rotation matrix is defined based on virtual source and receiver geometry (Figure 2a):

\[
\begin{pmatrix}
ZZ \\
ZR \\
RZ \\
RR
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \cos\theta_s & \sin\theta_s & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\cos\theta_r & 0 & 0 & -\sin\theta_r & 0 & 0 \\
0 & 0 & 0 & 0 & -\cos\theta_r & \cos\theta_s & -\sin\theta_r & \sin\theta_s & 0
\end{pmatrix}
\begin{pmatrix}
ZZ \\
ZN \\
ZR \\
NZ \\
RZ \\
RN \\
RZ \\
NR \\
ZZ
\end{pmatrix}
\]

where \(\theta_s\) and \(\theta_r\) are the bearings of the raypath at the virtual source (azimuth) and the receiver (back azimuth), respectively (Figure 2a). An example of NCFs calculated for the station pair, NE12-NE46, is shown in Figures 3a and 3b, which, respectively, show the positive and negative sides of the empirical Green functions filtered with an 8–25 s band-pass filter. The corresponding particle motions are shown in Figures 3c and 3d.

Figures 3c and 3d show the particle motions of the Rayleigh wave at station NE46, excited by virtual vertical and horizontal sources, respectively. Similarly, Figures 3e and 3f represent the particle motions of Rayleigh waves recorded at station NE12. Both stations exhibit an elliptical particle motion; however, the basin station NE46 (Figure 1) is characterized by a horizontal major axis, while the Great Xing’an range station NE12 (Figure 1) possesses a vertical major axis, indicative of significant difference in shallow structure beneath the two stations.

2.2. Earthquake Data

To measure Z/H ratio from earthquake data, we select ~400 earthquakes occurring between September 2009 and August 2011 with epicentral distances ranging between 10 and 140° and magnitudes greater than 6.0. We cut out the Rayleigh wave of each earthquake, remove the linear trend and mean for each component, and then band pass filtered the data at 8–50 s periods. We further decimate the data to one sample per second after applying an antialiasing filter to the data and rotate the two horizontal components to the radial and transverse directions. The radial and vertical components are finally selected to measure Z/H ratio in the period range of 10–40 s, which partially overlaps with the ambient noise period band of 8–25 s.

3. Methodology

3.1. Z/H Ratio Measurement

For the NCFs calculated for one virtual source-receiver station pair, the positive part is associated with the Green’s function traveling from the virtual source to the receiver, and therefore, the Z/H ratios measured from this part of the NCFs reflect the velocity structure beneath the receiver station. Similarly, the Z/H ratios measured from the negative side of the NCFs are expected to be associated with the velocity structure beneath the virtual source station. Thus, we did not stack the positive and negative sides of the NCFs but stacked the Green’s functions from a vertical and radial source to enhance the signal-to-noise ratio (SNR) in measuring the Z/H ratio (Appendix A).

The ZZ and ZR NCFs can be considered as the vertical and radial records at the receiver station due to a vertical force at the virtual source. Since we apply the normalization and whitening to the noise data of all the three components with the same temporal normalization functions and spectrum, the relative amplitude of the two NCFs is preserved in the cross-correlation calculation. Similarly, the RZ and RR NCFs are the vertical and radial records of radially directed force. Theoretically, Rayleigh wave radiated from a vertical or a radial point force is expected to have the same Z/H ratio. Since the maximum amplitude of the four NCFs (ZZ, ZR, RZ,
and RR) is in the same order of magnitude, therefore, we use the sum of ZZ and RZ as the numerator and the sum of ZR and RR as the denominator in computing the Z/H ratio:

\[ E(T) = \frac{A_{ZZ}}{A_{ZR}} = \frac{A_{H(ZZ+RZ)}}{A_{H(ZR+RR)}} \] 

(2)

Figure 3. Examples of the calculated NCFs of ZZ, ZR, RZ, and RR between station pair NE12 and NE46 with (a) NE12 as a virtual source and NE46 as a receiver and (b) vice versa. The NCFs are band-pass filtered at 8–25 s periods. (c and d) Particle motions of the Rayleigh wave recorded at NE46, excited by a vertical and radial source, respectively. (e and f) Same as Figures 3c and 3d except for NE12. Note that the low Z/H ratio station NE12 and the high Z/H station NE46 are located at the Great Xing’an range and the Songliao basin, respectively.
where \( E/T \) is the \( Z/H \) ratio for period \( T \), and \( A \) indicates the maximum amplitude of the Rayleigh wave. \( H[ZZ] \) and \( H[ZR] \) represent the Hilbert transform of the ZZ and ZR NCFs.

It is known that there is a 90° phase shift between the \( Z \) and \( R \) components (\( R \) minus \( Z \)) for Rayleigh waves recorded at both the virtual source and receiver stations (Figure 2b). Their cross-correlation functions, ZZ and RR NCFs, are expected to be in phase, while the ZR and RZ NCFs are, respectively, 90° ahead and 90° behind the ZZ and RR NCFs, i.e., for a monotonic Rayleigh wave with a period \( T \), the arrival times at the four NCFs are expected to have the following relationship (Figure 2c):

\[
t_{ZZ} = t_{RR} = t_{RZ} - T/4 = t_{ZR} + T/4
\]

Therefore, in order to stack ZZ and RR, a Hilbert transform is applied to ZZ to keep the two NCFs in phase. Similarly, we apply a Hilbert transform to ZR to delay its phase by 90° to align it with RR and then sum the two as the denominator.

For the selected Rayleigh wave time window, we first employ a phase-matched filter [Levshin and Ritzwoller, 2001] to the stacked \( Z \) and \( R \) components to eliminate noises from the data. The algorithm for estimating the \( Z/H \) ratio is adapted from Tanimoto and Rivera [2008]. Here we briefly describe the major steps. We first filter them with a series of Gaussian band pass with bandwidths that vary from 0.0025 to 0.0400 Hz depending on the central frequencies and source-receiver distances [Herrmann, 1973]. For each band-pass-filtered data, we compute the zero-lag cross-correlation coefficient of the vertical component and the phase-delayed radial component. We discard the data that have a zero-lag cross-correlation coefficient less than 0.8. If the narrowly band-pass-filtered data are selected, the envelopes of the two components are computed, and their maxima are used to calculate the \( Z/H \) ratio. Since we use the maximum of each component in computing the \( Z/H \) ratios, the phase-matched filtering appears to have little effect on our measurements.

To retain the most reliable measurements, we adopt the following additional criteria to further select the data.

1. We only select Rayleigh wave data with a SNR \( \geq 8 \) on both the stacked \( Z \) and \( R \) components. Here the SNR is defined as the max amplitude of the signal to the RMS of a 500 s long noise window defined from 3000 s after the Rayleigh wave [Bensen et al., 2007].
2. We only select station pairs with an interstation distance greater than three wavelengths to satisfy the far-field requirement for the ambient noise cross-correlation data [Bensen et al., 2007].
3. For each period, we require at least 20 \( Z/H \) measurements in order to get statistically robust average. Furthermore, we require that the distribution of the \( Z/H \) measurements roughly follow a Gaussian distribution with a standard error less than 15% of the average.
4. We further discard stations with less than five robust average \( Z/H \) estimates (i.e., at five periods).

We finally select 110 stations that satisfy the above criteria (i.e., 17 stations are dropped off), among which six stations show significant differences (\( \geq 10\% \)) in the measurement \( Z/H \) ratio between the NCFs and earthquake events data. We have examined possible causes for the observed discrepancy, including sensor misorientation and bias from event azimuthal distribution, but fail to obtain a good explanation. Therefore, we decide to leave this issue for further investigation and exclude these six stations in the joint inversion.

### 3.2. Joint Inversion of Dispersion and \( Z/H \) Ratio Data

We jointly invert phase velocity dispersion curves and ellipticities at period 8–40 s using a DRAM (Delayed Rejection Adaptive Metropolis) algorithm [Haario et al., 2006; Mira, 2001] based on Markov chain Monte Carlo (MCMC) method [Bodin et al., 2012; Afonso et al., 2013; Shen et al., 2013] to obtain 1-D \( S \) wave velocity depth profiles for each station. The Bayesian MCMC inversion method has been well discussed in several literatures, such as Bodin et al. (2012), Afonso et al. (2013), and Shen et al. (2013) and thus will not be described here. The basic principle of DRAM algorithm is to improve the MCMC algorithm by updating the acceptance probability of the new candidate model on a regular interval determined by previous samples in the chain, which could increase the probability of sampling regions with high posterior probability.

The phase velocity dispersion data are obtained from Guo et al. [2015]. Phase velocities at different period were first measured from ambient noise data and then inverted to 0.2° by 0.2° spatial grids across NE China. The dispersion data at each station are taken from the phase velocities of the closest grid. The \( Z/H \) ratios are measured at each station and are obtained from ambient noise data for periods less than 25 s and from earthquake events for periods longer than 25 s. Both data sets are expected to reflect mainly the seismic velocity structure beneath each station and thus can be jointly inverted to obtain the seismic structure underneath the stations.
Table 1. Model Space and References

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment thickness</td>
<td>0–2m0 (km)</td>
<td>Laske and Masters [1997]</td>
</tr>
<tr>
<td>VSu, top of sedimentary layer</td>
<td>1.0–3.5 (km)</td>
<td>Guo et al. [2015]</td>
</tr>
<tr>
<td>VSu, bottom of sedimentary layer</td>
<td>1.0–3.5 (km)</td>
<td>Guo et al. [2015]</td>
</tr>
<tr>
<td>Crystalline crustal thickness</td>
<td>m0 ± 5 (km)</td>
<td>Tao et al. [2014]</td>
</tr>
<tr>
<td>B-spline coefficients, crust</td>
<td>m0 ± 0.2m0 (km/s)</td>
<td>Guo et al. [2015]</td>
</tr>
<tr>
<td>B-spline coefficients, mantle</td>
<td>m0 ± 0.2m0 (km/s)</td>
<td>Dziewonski and Anderson [1981]</td>
</tr>
</tbody>
</table>

The 1-D shear velocity model consists of a sedimentary layer, a crystalline crustal layer, and a mantle layer along the depth direction, which is delineated by 13 independent parameters (Table 1). The sediment layer has three parameters: thickness and velocities at top and bottom of the layer. The crustal layer is described by five parameters including Moho depth and four cubic B-splines to represent the vertical variation of Vp. The mantle is characterized by five cubic B-splines to represent Vp variations. For the sedimentary layer, we set Vp/Vs ratio to 2.0 and initial sediment thickness is taken from Laske and Masters [1997]. The crystallal Vp/Vs ratio and initial Moho depth are taken from Tao et al. [2014]. In the upper mantle, we choose a constant Vp/Vs ratio of 1.732. We also employ Birch’s law of Vp = 3.125ρ − 2.40 (ρ: g/cm³, Vp, Vs: km/s) [Birch, 1961] to tie density ρ to Vs to be inverted through Vp. A prior constraint is imposed to the Vs contrasts across the sediment base and the Moho, forcing them to be positive (i.e., sedimentary Vs < upper crust Vs and lower crust Vs < mantle Vp).

Phase velocity dispersion curves and ellipticities are modeled using the MINEOS [Masters et al., 2007]. The misfit of the joint inversion (MJOINT) is defined as

\[ M_{\text{JOINT}} = c_1 M_{5W} + c_2 M_{ZH} \]

\[ = c_1 \sum_{i=1}^{N} \left[ \frac{G_i(m) - D_i^{\text{obs}}}{\sigma_i} \right]^2 + c_2 \sum_{j=1}^{M} \left[ \frac{R_i(j) - R_j^{\text{obs}}}{\gamma_j} \right]^2 \]  

(4)

Here \(G_i(m)\) is the calculated phase velocity from model \(m\) at period \(i\) on a discrete grid of \(N\) periods. \(D_i^{\text{obs}}\) is the observed phase velocity at the same period. The \(R_i(j)\) is the predicted \(Z/H\) ratio of model \(m\) at period \(j\) on a discrete grid of \(M\) periods, and \(R_j^{\text{obs}}\) is the observed \(Z/H\) ratio at the same period. \(\sigma_i\) and \(\gamma_j\) represent the uncertainties of phase velocity at period \(i\) and \(Z/H\) ratio at period \(j\), respectively. The weighting factors of two data sets are set to be equal \((c_1 = c_2 = 0.5)\).

The initial models are constructed based on the results of Guo et al. [2015] for the upper 80 km and the preliminary reference Earth model [Dziewonski and Anderson, 1981] between the depths of 80 and 200 km. Below 200 km, the velocities are set to be constant. We also assume an isotropic velocity model in the joint inversion. Since the longest period of our data is 40 s (Figure 8b), which has a depth resolution limited to the uppermost mantle, thus we only invert Vs above 80 km.

For each station, we first randomly generate 100,000 models and compute their misfits according to equation (4). We then choose 2000 models with the lowest misfits to estimate the final inversion result. The final 1-D velocity is obtained by averaging the 2000 models.

4. Results and Discussion

4.1. The Measured Z/H Ratios

Figure 4 shows the histogram of \(Z/H\) ratio of 15 s Rayleigh wave measured from NCFs (Figure 4a) and earthquake data (Figure 4b) at station NE11, with both data sets following the Gaussian distribution. We compute their averages and standard deviations of the means and use them as the \(Z/H\) ratio estimates and uncertainties.

Figure 5 shows the \(Z/H\) ratios at six stations measured from NCFs (red solid points) and earthquake data (blue points) with the estimated error bars. Stations NE11, NE46, and NE73 are located inside the basins, while stations NE12 and NE53 are based on the Great Xing’an range. The measured \(Z/H\) ratios at the basin stations appear to be relatively low at short periods (10–20 s) but increase substantially with increasing period. On the contrary, the \(Z/H\) ratios measured from mountainous areas are comparatively higher at short periods (10–20 s) but
Figure 4. The distributions of all Z/H ratios of 15 s Rayleigh wave measured from (a) ambient noise and (b) earthquake data at station NE11. The calculated average value and standard error are listed at the top right corner of each plot.

Figure 5. The measured Z/H ratios at six stations (see their location in Figure 1) as a function of period, with blue and red points representing measurements from ambient noise and earthquake data, respectively. Uncertainties are indicated by vertical bars. These stations are (a) NE11, (b) NE12, (c) NE46, which are located in the southern Songliao basin, and (d) NE53, (e) NE73, (f) NE34 that are situated at the Great Xing'an range. Note the Z/H ratios at station NE34 in Figure 5f measured from NCFs and earthquake data differ significantly from each other.
decrease slightly with increasing period. At longer periods (>30 s), the Z/H ratios become relatively stable in both the mountain and basin areas. One interesting phenomenon is that the Z/H ratios measured from NCFs seem to be smoother than those from earthquake data at short periods, possibly related to the fact that short-period Rayleigh waves from earthquakes are noisier resulting from scattering and attenuation after long-distance travel.

Figure 6. Maps of the Z/H ratios at four different periods, 10, 15, 20, and 25 s, measured from (a, c, e, and g) ambient noise and (b, d, f, and h) earthquake data, respectively.
propagation. In general, the $Z/H$ ratios measured from NCFs and earthquake data agree well with each other at most stations, except a few stations that are marked by yellow triangles in Figure 1. Figure 5f shows one example of such station, NE34, whose $Z/H$ ratios measured from the two types of data sets are significantly different. As mentioned before, we have investigated the causes for such a discrepancy and are not able to find an obvious issue to explain it; thus, we would like to leave this to future studies.

In Figure 6, we present maps of the observed $Z/H$ ratios at four periods measured by ambient noise and earthquake data. In each map, triangles denote the stations at which the measured $Z/H$ ratios are used for the interpolation. The left panel shows the maps of the $Z/H$ ratios measured from NCFs, while the right column are the corresponding $Z/H$ ratios estimated from earthquake data. A comparison of the two columns suggests that the $Z/H$ ratios derived from earthquake data (Figures 6a, 6c, 6e, and 6g) are generally higher than those estimated from NCFs (Figures 6b, 6d, 6f, and 6h). One possible reason could be related to off great circle path propagation effects caused by structural anomalies, which are expected to be larger in the earthquake data due to the relatively longer raypaths. The off great circle path propagation can consistently lower the radial amplitude and therefore results in higher than actual $Z/H$ ratios. However, the difference between the NCFs and earthquake data are small that the two columns seem to be very similar to each other, suggesting that $Z/H$ ratios can be robustly extracted from the two types of data with proper processing techniques.

All the maps show that the $Z/H$ ratios inside the Songliao basin are distinctly lower as compared to its surrounding areas. This contrast fades away gradually with increasing period.

We adopt the method proposed by Lin et al. [2009] to estimate the uncertainties of $Z/H$ ratio. Lin et al. [2009] suggest the uncertainty in the measured $Z/H$ ratio can be approximated by 1.5 times of the standard deviation from the statistical mean. Figure 7 presents the uncertainty maps of the $Z/H$ ratios computed with the above method at periods 10 s and 25 s using measurements from the NCFs and earthquake data. At 10 s, the measurement with earthquake data exhibits much larger uncertainties, especially inside the basins, as

Figure 7: Maps showing the uncertainties of the $Z/H$ ratio measurement at periods (a and b) 10 s and (c and d) 25 s, using NCFs (Figures 7a and 7c) and earthquake data (Figures 7b and 7d), respectively.
compared to the ambient noise data (Figures 7a versus 7b). But at 25 s, the uncertainties in the $Z/H$ ratio measurements from the two types of data are comparable and smaller.

### 4.2. The 3-D Velocity Model and Discussions

Figure 8 shows the sensitive kernels of the phase and ellipticity at period 8 s and 40 s. Those kernels are produced during the joint inversion of station NE11. As mentioned above, we employ a fixed $V_p/V_s$ ratio ($V_p = 2.0V_s$ for the sedimentary layer or $V_p = 1.732V_s$ for other layers) and a scaling law between velocity and density ($\rho = (2.400 + 1.732V_s)/3.125$ for sedimentary layer or $\rho = (2.400 + 1.732V_s)/3.125$ for other layers) in our inversion for $S$ wave velocity beneath each station. Here we also use these assumed scaling relationships in computing the phase velocity and $Z/H$ ratio kernels. Our main purpose here is to illustrate the sensitivity difference to depth between the two types of kernels; thus, sensitivity kernels to the $P$ wave velocity and density are not shown here. The two phase velocity kernels reach their maxima at roughly one third of their wavelengths. The two $Z/H$ kernels, on the other hand, have their peak sensitivity at zero depth, which explains why $Z/H$ ratios are better observables to constrain shallow structures than the dispersion data.

At each station, we jointly invert the dispersion and $Z/H$ ratio data for a 1-D $S$ wave velocity model. Figure 9 shows two examples of the inverted 1-D velocity models beneath station NE12 and NE46. Both the dispersion and $Z/H$ ratio data are well fitted. Once we invert the 1-D velocity models at all the stations, we employ a minimum curvature surface-fitting method [Smith and Wessel, 1990] to interpolate the results onto 0.5° by 0.5° grids covering our study region from 41° to 48.5° in latitude and from 115° to 134° in longitude to form the final 3-D velocity model. We remove areas that are more than 150 km away from the nearest station.

Figure 10a shows the velocity variations at 1 km beneath the surface. For comparison, we also show the $S$ wave velocity at the same depth inverted from phase dispersion data alone in Figure 10b. We notice two distinct differences between the two maps. The $S$ wave velocities inside the basins derived from the joint inversion are significantly lower than those from the dispersion inversion. The lowest $S$ wave velocities at the 1 km depth obtained by the joint and dispersion inversions are, respectively, 1.22 and 1.72 km/s, and the averaged $S$ wave velocities within the Songliao basin at the same depth are 1.91 and 2.36 km/s. The differences are at the ~20–35% level. The boundaries that outline the low-velocity anomalies are very sharp and match very well with the basins, such as the Songliao, Sanjiang, and Erlian basins. There is only one station located inside
the Hailar basin; thus, the structure beneath it is not well resolved in this study. Such an excellent correlation between the low-velocity areas and the basin, however, is not so clear in the velocity map (Figure 10b), which is inverted from phase velocity dispersion data only. The comparison clearly demonstrates the resolving power of the \( Z/H \) ratio data on shallow structures. This excellent correlation between the Songliao basin and the strong low-velocity anomaly extends to at least 4 km deep, where we observe a NW-SE trending ridge with normal velocities that separates the basin into the northern and southern parts (Figure 10c). The slow anomaly beneath the northern Songliao basin appears to extend to at least ~6–7 km (Figures 10d and 10e). The difference in sedimentation between the northern and southern Songliao basin can be further seen in the depth cross sections plotted in Figure 11. The geographic locations of these cross sections are shown in Figure 10c. AA’ is an EW section taken along the 43.5°N latitude, which samples the southern Songliao basin. The low-velocity sediment is approximately 3 km thick in the west side and shallows gradually toward east, where the sediment is ~2 km thick (Figure 11a). The BB’ line sampling the northern Songliao basin shows a similar westward dipping trend (Figure 11b). The sediments in the west are, however, twice as thick as those in the southern Songliao basin. The S wave velocities at shallow depth beneath the northern Songliao basin (~1.4 km/s) are nearly 30% lower than those in the southern Songliao basin (1.8 km/s). We notice that these two depth sections agree very well with the results of two active seismic profiles roughly at the same locations shown in Figure 3 of Wei et al. [2010]. The contrast between the southern and northern Songliao basin can be further seen in the CC’ section (Figure 11c), which samples the basin along its NE-SW strike. In Figure 11d, we further show a NEE-SWW trending depth section that samples the Erlian, northern Songliao, and Sanjiang basins. The low-velocity sediments are clearly shown beneath the three basins.

**Figure 9.** Two examples of the joint inversion combining dispersion and \( Z/H \) ratio data. (a and b) The fitting of \( Z/H \) ratio and phase velocities at station NE12. Black points with vertical error bars connected by thin black lines represent the measured data, while the red lines indicate \( Z/H \) ratios and phase velocities calculated from the inverted S wave velocity model. (c and d) Similar to Figures 9a and 9b except for station NE46. (e) The final 1-D S wave velocity models beneath the two stations, NE12 and NE46, are shown in red and green, respectively. The two models are calculated by averaging the velocity structure of the 2000 best fitting models.
In the lower crustal depth, the most distinct feature is the low velocity beneath the great Xing’an range (Figure 10f). This low-velocity anomaly becomes even stronger at 32 km deep (Figure 10g). At this depth, we also observe a very strong high-velocity structure at the eastern edge of the Songliao basin where the thinnest crust of the study area is located based on Tao et al. [2014]. Thus, the velocity contrast between the eastern Songliao and great Xing’an reflects the velocity difference between mantle and crust. In the uppermost mantle (Figures 10h and 10i), low-velocity anomalies beneath the southern Xing’an range, the Jiamusi Massif, and the Changbaishan volcanic complex are the dominant features, which are clearly linked to magmatic activities.

The most distinct features shown in the jointly invert 3-D velocity model are the substantial low velocity beneath the basins and the strong contrast in sedimentary structure between the southern and northern Songliao basin. The southern Songliao basin is generally considered as a wide rift system developed from the Late Jurassic to Early Cretaceous [Wei et al., 2010]. Previous geologic and active source seismic studies [e.g., Feng et al., 2010; Wei et al., 2010] suggest that the southern Songliao basin is marked by substantial synrift subsidence but insignificant postrift subsidence. The northern Songliao basin, on the other hands, appears to have a distinct tectonic subsidence history characterized by significant synrift and postrift sedimentation; the latter can reach as thick as 4 km. The insignificance of postrift subsidence of the southern Songliao basin is consistent with the observations made in this study.
Figure 11. Four cross-sections of the jointly inverted 3-D S wave model. The geographic locations of these cross sections are delineated in Figure 10c. (a and b) S wave velocities across the southern and northern Songliao basin. (c) A cross section that samples the Songliao Basin along its strike direction, illustrating the difference in sedimentary structure between southern and northern Songliao basin. (d) A NEE-SWW trending depth section that shows the structure beneath the Erlian and northern Songliao and Sanjiang basins.
Songliao basin is difficult to invoke pure shear extensional mechanism [McKenzie, 1978], which predicts a considerable thermal subsidence following initial rifting. Wei et al. [2010] proposed that the low subsidence rate observed in the southern Songliao basin could be caused by inflow of low-crustal materials from surrounding highly elevated mountain regions. The great Xing’an range is characterized by large-scale Mesozoic magmatism, which is dominantly granitic as observed at the surface. Granitic rocks with several kilometers thick cover most part of the Great Xing’an range [Wu et al., 2003a, 2003b]. In particular, we observe a strong low-velocity anomaly beneath the southern end of the Great Xing’an range, which extends from the middle crust to the uppermost mantle. This suggests that temperature at lower crustal depths is relatively high, which can significantly reduce the viscosity of lower crust, making it easy to flow to its eastern neighbors, the southern Songliao basin that has a low elevation. Thus, our 3-D velocity model is consistent with this lower crustal flow mechanism to explain the low level of post rift sedimentation inside the southern Songliao basin. However, Tao et al. [2014] argued that this scenario has a problem in explaining the low to normal crustal $V_p/V_s$ ratio in the southern Songliao basin. In general, if crustal thickening were accomplished by injection of lower crustal materials, then one would expect to observe a positive correlation between crustal thickness and $V_p/V_s$, ratio, as mafic lower crustal rocks tend to have high $V_p/V_s$ ratios. The positive correlation was, however, not observed in the measured $V_p/V_s$ ratio.

The small post rift subsidence can be due to uplift forces coming from the mantle. Tao et al. [2014] found that southern Songliao basin has a slightly positive residual topography (~0.25 km) that cannot be explained by the Airy isostasy model. Volcanic rocks erupted during 86–39 are mainly found in the southern Songliao basin [Liu et al., 2001], suggesting that a mantle upwelling was present beneath that part of the basin after the rifting in late Jurassic and early Cretaceous, which jeopardized the afterward thermal subsidence that have otherwise occurred. Liu et al. [2015] found significant difference in the subduction geometry of the Pacific slab in the transition zone between the southern and northern Songliao basin. The Pacific slab is under stagnant subduction in the north but not in the south. Slab segmentation might have occurred beneath the southern Songliao basin, allowing hot asthenospheric material trapped under the subducting Pacific plate to rise to the upper mantle through the edge of the Pacific slab near the upper and lower mantle boundary [Tang et al., 2014]. Thus, we believe that the low post rift subsidence rate in the southern Songliao basin has a plausible deep origin in the mantle.

5. Conclusions

In this study, we measure the Rayleigh wave $Z/H$ ratio in the period band of 8–40 s from ambient noise and earthquake data recorded by the NECESSArray in NE China. At short periods, measured $Z/H$ ratio at basin stations is significantly lower than those in surrounding areas. We jointly invert the measured $Z/H$ ratios and phase velocity dispersion data for a high-resolution 3-D $S$ wave velocity model of NE China. Compared to the 3-D model inverted from dispersion data alone, our model exhibits the following two distinct features: (1) the shallow low-velocity anomalies possess much stronger amplitude and have a better correlation with the sedimentary basins in the area; (2) the southern Songliao basin is characterized by thin and moderately low-velocity sedimentary structure, while the sediments in the northern Songliao basin are thick and of very lower wave velocity, a striking contrast that is consistent with previous results derived from active source $P$ wave data. Combining the results from previous passive source seismic studies [e.g., Tao et al., 2014; Liu et al., 2015], we propose that the insignificant amount of post rift subsidence observed inside the southern Songliao basin is likely caused by a mantle upwelling associated with the Pacific subduction.

Appendix A

For a station pair A and B, we first use station B as the reference station to compute the cross correlations: $Z_BZ_A$, $Z_BR_A$, $R_BR_A$, and $R_BR_A$. Here A and B represent stations and Z and R indicate the vertical and radial directions. The positive parts of the four cross correlograms ($Z_BZ_A$, $Z_BR_A$, $R_BR_A$, and $R_BR_A$) can be considered as the vertical and radial components of the Rayleigh waves recorded at station A generated by a point source at station B in the vertical and radial directions, respectively. Based on reciprocity principle of Green’s function, their negative sections ($Z_BR_A$, $R_BR_A$, $Z_BZ_A$, and $R_BR_A$) can be considered as the vertical and radial
components of the Rayleigh waves recorded at station B generated by a point source at station A in the vertical and radial directions, i.e.,

\[ \begin{align*}
Z_BZ_A^- &= Z_BZ_A^+ \\
R_BZ_A^- &= Z_BR_A^+ \\
Z_BR_A^- &= R_BR_A^+ \\
R_BR_A^- &= R_BR_A^+ .
\end{align*} \]

(A1)

This is also true for the cross correlograms computed with station A as the reference station, \( Z_AZ_B \), \( Z_AR_B \), \( R_AR_B \), and \( R_BR_B \), for which the negative portions can be considered as the Green’s functions at station A from a source at B:

\[ \begin{align*}
Z_AZ_B^- &= Z_AZ_B^+ \\
R_AZ_B^- &= Z_AR_B^+ \\
Z_AR_B^- &= R_AR_B^+ \\
R_AR_B^- &= R_AR_B^+ .
\end{align*} \]

(A2)

Therefore, the \( Z/H \) ratio at station A can be computed using either the two positive parts of the BA correlograms

\[ E_A = \frac{A_{Z_AZ_B^+}}{A_{Z_AR_B^+}} = \frac{A_{R_AR_B^+}}{A_{R_AR_B^+}} . \]

(A3a)

or the two negative parts of the AB correlograms:

\[ E_A = \frac{A_{Z_AZ_B^-}}{A_{Z_AR_B^-}} = \frac{A_{R_AR_B^-}}{A_{R_AR_B^-}} . \]

(A3b)

Based on equation (A2), equation (A3a) is identical to equation (A3b); thus, the positive parts of the BA correlograms are enough to estimate the \( Z/H \) ratio at station A.

Acknowledgments

We would like to thank all the people involved in the NECESSArray project and Steve Grand from UT Austin for their helpful discussion. The data of the NECESSArray project used by this paper are available at http://ds.iris.edu. We also thank Fan-Chi Lin and another anonymous reviewer for their constructive comments and suggestions, which significantly improved the quality of this paper. G.L., H.C., F.N. are supported by the Australian Research Council Discovery grant (DP120103673). This is contribution 695 from the ARC Centre of Excellence for Core to Crust Fluid Systems (www.ccfs.mq.edu.au) and 1052 in the GEMOC Key Centre (www.gemoc.mq.edu.au).

References


Liu, J., J. Han, and W. S. Fye (2001), Cenozoic episodic volcanism and continental rifting in northeast China and possible link to Japan Sea development as revealed from K–Ar geochronology, Tectonophysics, 339(3), 385–403.


