United Nations Educational, Scientific and Cultural Organization
and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

HIGH RESOLUTION RAYLEIGH WAVE GROUP VELOCITY TOMOGRAPHY
IN NORTH-CHINA FROM AMBIENT SEISMIC NOISE

Lihua Fang
Institute of Geophysics, China Earthquake Administration,
Beijing, People’s Republic of China
and
Department of Earth Sciences, University of Trieste, Trieste, Italy

Jianping Wu, Zhifeng Ding
Institute of Geophysics, China Earthquake Administration,
Beijing, People’s Republic of China

and

G.F. Panza
Department of Earth Sciences, University of Trieste, Trieste, Italy
and
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

MIRAMARE – TRIESTE
March 2009

1 flh@cea-igp.ac.cn
Abstract

This study presents the results of the Rayleigh wave group velocity tomography in North-China performed using ambient seismic noise observed at 190 broadband and 10 very broadband stations of the North-China Seismic Array. All available vertical component time-series for the 14 months span between January, 2007 and February, 2008 are cross-correlated to obtain empirical Rayleigh wave Green functions that are subsequently processed, with the multiple filter method, to isolate the group velocity dispersion curves of the fundamental mode of Rayleigh wave. Tomographic maps, with a grid spacing of 0.25°×0.25°, are computed at the periods of 4.5s, 12s, 20s, 28s. The maps at short periods reveal an evident lateral heterogeneity in the crust of North-China, quite well in agreement with known geological and tectonic features. The North China Basin is imaged as a broad low velocity area, while the Taihangshan and Yanshan uplifts and Ordos block are imaged as high velocity zones, and the Quaternary intermountain basins show up as small low-velocity anomalies. The group velocity contours at 4.5s, 12s and 20s are consistent with the Bouguer gravity anomalies measured in the area of the Taihangshan fault, that cuts through the lower crust at least. Most of the historical strong earthquakes (M≥6.0) are located where the tomographic maps show zones with moderate velocity gradient.
INTRODUCTION
The North China Craton (NCC), one of the oldest cratons on the Earth reached stability in the Paleoproterozoic (~1.86Ga). The eastern part of NCC had experienced significant tectonic rejuvenation in the late Mesozoic and Cenozoic with dramatic regional variations, which is evidenced by the widespread lithospheric extension, voluminous magmatism and large-scale basin formation (Griffin et al., 1998; Menzies & Xu, 1998; Fan et al., 2000; Xu, 2001). During this period, the thick cratonic lithosphere (>180 km) lost a significant proportion of its deep mantle keel (Menzies et al., 1993; Griffin et al., 1998). Geothermal studies, petrologic and isotopic data from Tertiary basalts as well as entrained mantle xenoliths, imply that the Cenozoic lithosphere is thinned to only 70–80 km (Hu et al., 2000; Xu, 2001; Xu et al., 2004). Many hypotheses and models have been put forward to interpret the Mesozoic destabilization and present complex lithospheric structure of the eastern China continent. These hypotheses include delamination, thermal and chemical erosion of the lithosphere, mantle plume and basaltic underplating (e.g., Tian et al., 1992; Gao et al., 1993, 2004; Xu, 1999, 2001; Deng et al., 1998, 2004; Zhang & Sun, 2002). But, because of the lack of high-resolution velocity models, especially shear wave velocity structure, these hypotheses haven't yet been satisfactorily tested against geophysical data and remain controversial.

The study region is located at the eastern margin of NCC (Fig. 1). The central part of the study area is NCB (North China Basin). NCB is a large epicontinental basin where many uplifts and depression basins developed since Cenozoic. NCB can be divided in two major internal uplifts (Chengning, Cangxian) and four major depressions (Jizhong, Huanghua, Jiyang, and Linqing) (Chang, 1991). The northeastern part of the study area is occupied by the relatively stable Yanshan uplift with its major structure and tectonic trend oriented in the E-W direction. The western and northwestern portions are taken by the Taihangshan uplift region with some small intermountain basins. To the southeast there is the Luxi Uplift, and to the east the Bohai Bay. In the NCB and the Taihangshan uplift region there are many active faults, oriented in the NE–SW direction. In the two regions, most of the structures and mountain ranges have trends oriented in the NE–SW direction.

This region is one of the most seismic active areas in China. Historical strong earthquakes occurred frequently in this area. More than 200 earthquakes with magnitude greater than 5.0 have occurred in this region since 780 BC, among them 37 events are larger than M= 6.0 and 10 events are larger than M= 7.0 (The Earthquake Disaster Prevention Department of China Earthquake Administration, 1995, 1999; China Earthquake Networks Center, 2008). In 1679, an earthquake of M= 8.0 occurred in Sanhe, which is the largest one among the known historical earthquakes in this region. The 1976 Tangshan earthquake (M=7.8) killed at least 240,000 people, and was one of the most destructive earthquakes in the world in human history.
Extensive geophysical investigations have been conducted in the NCC using the seismic reflection and refraction experiment (Li et al., 2006) and body wave tomography method (Huang & Zhao, 2004; Qi et al., 2006; Lei et al., 2008). However, these previous results are mainly concentrated on P wave velocity structure. The receiver function method has been applied to study the shear wave velocity structures, but can only give the velocity structures beneath the stations (Zheng et al., 2005; Wang et al., 2009). Many surface wave tomography studies have also been conducted (e.g., Feng & Teng, 1983; Ritzwoller & Levshin, 1998, Huang et al., 2003), but most of them are at China mainland scale and the lateral resolution is in the order of 100-200km. Yet few studies of surface waves in North-China have been undertaken to date, which is due to the relatively low level of seismicity and the consequent logistic limitation suffered by earthquake-based surface wave tomography. Previous studies almost exclusively used teleseismic earthquakes. It is difficult to obtain reliable short-period (<10 s) dispersion measurements from distant earthquakes due to intrinsic attenuation and scattering along the ray paths, and it is these short-period waves that are most useful for constraining the structure of the crust and uppermost mantle. Moreover, the long paths also result in broad lateral sensitivity kernels which limit resolution to hundreds of kilometers. For these reasons, high-resolution surface wave tomography results are scarce.

In order to study the formation and evolution of NCC, to obtain crust and upper mantle structure and to verify various proposed mechanisms for the interpretation of the lithospheric process which occurred in NCC, knowledge about the fine-scale crustal structure is needed. A recent temporary deployment of a broadband seismic array (North China Seismic Array, NCSA) offers abundant high-quality data to achieve this goal. Besides, the newly developed ambient noise tomography (ANT) method also makes it possible to obtain high-resolution shear wave velocity structure.

Experimental and theoretical studies have shown that Green function between two points can be estimated from the cross correlation of recordings made at the two locations (Weaver & Lobkis, 2001; Derode et al., 2003; Larose et al., 2005; Snieder, 2004; Wapenaar, 2004). Shapiro & Campillo (2004) demonstrated that Rayleigh wave empirical Green functions (EGFs) estimated from ambient noise possess dispersion characteristics similar to earthquake derived measurements and model predictions. The dispersion characteristics of surface wave EGFs derived from ambient noise can be used to produce dispersion tomography maps. The ANT method alleviates some of the problems affecting traditional surface wave measurements made on teleseismic earthquake recordings. This method has been successfully applied in several geographical settings, such as Southern California (Shapiro et al., 2005; Sabra et al., 2005), Tibet (Yao et al., 2006), Europe (Yang et al., 2007), New Zealand (Lin et al., 2007), China mainland (Zheng et al., 2008), and elsewhere in the world, also at very local scale (e.g. De Nisco et al., 2008).
NCSA provides a nearly ideal network for the application of ambient noise tomography. Station density is approximately uniform across the network, and excellent spatial and azimuthal coverage emerges from interstation paths. In this study, we apply the cross-correlation technique to the ambient noise data for each station pair recorded by NCSA. Rayleigh wave group velocity dispersion curves are measured at periods from 4s to 40s from the cross-correlations. Surface wave tomography is conducted to generate group velocity maps and the features of group velocity space distribution at different periods are analyzed. The relationships between Bouguer gravity anomaly, seismicity and tomographic map are discussed. These maps display higher resolution and span to shorter periods than previous surface wave tomography maps; to the authors' knowledge, the resolution presented here is, so far, the highest one in the China mainland.

**DATA PROCESSING**

In order to study the decratonization (Yang et al., 2008) and the deep structure of NCC, a seismic experiment (NCSA) has been carried out since the winter of 2006. 250 portable stations were deployed in North China, of which 190 are broadband stations, 10 are very broadband stations and 50 are short period stations. Each station is equipped with Reftek-130B digitizer. The average station separation is about 35 km. Continuous vertical-component seismograms, spanning the period from January 1, 2007 to February 28, 2008 recorded by 190 broadband stations and 10 very broadband stations, are used in this study (Fig. 4).

By restricting the data processing to vertical component waveforms, we recover only Rayleigh wave. The data processing procedure that is applied here is very similar to that described in detail by Bensen et al. (2007). Here we summarize it briefly. Data are processed one day at a time for each station after being decimated to 1 Hz, bandpass filtered in the period band from 4 to 100 s and after the daily trend, the mean and the instrument response are removed. Instead of using one-bit normalization method, we apply the running-absolute-mean method to the data. The running average is computed between 15s and 50s and the normalization window is 50s in duration. The last step of pre-processing is to whiten the data over the frequency-band of interest. Then the day-long waveform at each station is correlated with that at each of the other stations and the daily results are stacked to produce the final cross correlation.

The resulting cross-correlations contain surface wave signals coming from opposite directions along the path linking the stations. The cross correlations are often asymmetrical due to the inhomogeneous distribution of ambient noise sources. To simplify data analysis and enhance the signal to noise ratio (SNR), we average the positive and negative lags of the cross correlation to form ‘symmetric signals’. The following analysis is done on the symmetric signals exclusively. Fig. 2 shows an example of 14-month stacks of cross-correlations plotted as a record-section. Clear signals are seen for both positive and negative correlation lags with physically reasonable
moveouts ($\sim 3$ km·s$^{-1}$).

**DISPERSION MEASUREMENT AND TOMOGRAPHY**

Rayleigh wave group velocity dispersion curves are determined using a multiple filter method (Dziewonski et al., 1969; Levshin et al., 1992; Liang et al., 2008). The implementation of this process is illustrated in Fig 3. Fig. 3(a) is the original cross correlation waveform (cross correlation between GUY station and CHL station). The original seismogram is filtered using a series of Gaussian filters with central periods ranging from 4s to 50s. The envelope functions of the filtered seismograms, i.e., the FTAN spectrum, are plotted in Fig. 3(b) with colors representing envelope amplitudes. This method constructs a 2-D diagram of signal power as a function of time or group velocity and the central frequency or period of successive narrow-band Gaussian filters. The local power maximum along the period axis is picked. The group arrival times of the maximum amplitude as a function of filter period are used to calculate a group velocity curve.

A generalized 2D-linear inversion procedure developed by Ditmar & Yanovskaya (1987) and Yanovskaya & Ditmar (1990) has been applied to construct the group velocity tomographic maps. This method is a generalization to two dimensions of the classical one-dimensional method of Backus & Gilbert (1968). The result of surface wave tomography is the estimation of local values of group velocity at different knots over the study region, which can be used to obtain group velocity maps for different periods.

The tomographic method estimates a group velocity map $U(x)$ at each period by minimizing the following misfit function:

$$
\alpha \iint |\nabla m(x)|^2 dx + (d - Gm)^T (d - Gm) = \min,
$$

where,

$$
m(x) = (U^{-1}(x) - U_0^{-1})U_0, \tag{2}
$$

$$
d_i = t_i - t_{i0}, \tag{3}
$$

$$
(Gm)_i = \iint G_i(x)m(x)dx = \int_{t_{i0}}^{t_i} m(x) \frac{ds}{U_0}, \tag{4}
$$

$$
\iint G_i(x)dx = \int_{t_{i0}}^{t_i} \frac{ds}{U_0} = t_{i0}, \tag{5}
$$

In the relations (1–5), $x = x(\theta, \phi)$ is the position vector, $U_0$ is the velocity corresponding to a starting model, $t_i$ is the observed travel time along the $i_{th}$ path, $t_{i0}$ is the travel time
calculated for the starting model, $\alpha$ is a regularization parameter, $l_{ij}$ is the length of the $i_{th}$ path and $s$ is the segment along which the inversion is performed. The parameter $\alpha$ controls the trade-off between the fit to the data and the smoothness of the resulting group velocity maps.

**DATA SELECTION**

The number of inter-station path grows as the square of the number of stations, but not all paths can be used to obtain a high quality dispersion curve, so it's not possible to make dispersion measurements for all the paths. In order to get a reliable tomography result and minimize workload, some data quality control criteria must be devised to identify and reject bad measurements. In this study, we use four criteria to select data, which are minimum inter-station distance, signal to noise ratio, cluster analysis and traveltime residual.

First, we apply a minimum three wavelengths inter-station distance constraint and we exclude paths shorter than 120 km, which is imposed by the measurement instabilities at short distances. Since the average inter-station path length is about 300 km in NCSA, the minimum wavelength criterion significantly reduces the number of measurements at periods above 30 s because stations must be separated by more than 360 km.

Second, we apply a selection criterion based on the period-dependent SNR, which is defined as the peak signal in a signal window divided by the root mean square (RMS) of the trailing noise, filtered with a 10-30s bandpass filter. The Rayleigh wave signal window is calculated by the inter-station distance divided by the group velocity windows (2-5 km/s). We store the cross correlations from -1500s to 1500s. The noise window is defined from 1000s to 1500s. We only select cross correlations with $\text{SNR} \geq 7$ and measure their dispersion curves.

Third, we apply clustering analysis to dispersion curves retrieved from ambient noise data. Clustering measurements obtained at a particular station from a set of earthquakes located near to one another is commonly used to assess uncertainties in earthquake dispersion measurements (e.g. Ritzwoller & Levshin, 1998; Pontevivo & Panza, 2002; 2006). We select dispersion curves with similar azimuths and similar distances obtained at a station. These dispersion curves are considered to be similar to each other, because they almost sample the same region. In some cases, one can get a very smooth, continuous but dubious dispersion curve. By using clustering analysis, we can verify the reliability of this kind of measurement and discard the questionable ones.

The last criterion on the quality of the solution is the comparison of the initial mean square travel time residual and the remaining (unaccounted) residual, $\sigma$. Since it has been assumed that the unaccounted residuals are random, $\sigma$ can be accepted as an estimate of the standard error of the data, which allows the computation of the standard error of the solution, $\sigma_m$. The value of $\sigma$ is also used in this study for the selection of the appropriate data. If an individual value of the travel time residual is larger than $3\sigma$, the corresponding path is eliminated from the data set and the
solution is recalculated (Yanovskaya et al., 1998). The histograms of the remaining residuals for the four periods are shown in Fig. 7. The RMS of the initial travel-time residuals is about 5s and the RMS of the final unaccounted residuals is about 2s. These values are fairly small compared to those obtained when earthquakes are used in tomography.

The number of dispersion curves after data selection at 4.5s, 12s, 20s and 28s is 1528, 4445, 2983 and 846, respectively. The distribution of the ray-paths at 12s period is shown, as an example, in Fig. 7.

RESOLUTION
As with any tomographic inversion, the resulting maps are not uniquely defined because the initial data do not constrain the seismic velocities at all points of the medium. Therefore, the knowledge of the resolving power is important in order to estimate the minimum really resolvable feature by a given data set and to sort out those features that may be numerical artifacts. Yanovskaya (1997) and Yanovskaya et al. (1998) proposed to use two parameters to estimate the lateral resolution: the mean size and the stretching of the averaging area.

A function \( S(x,y) \) for different orientations of the coordinate system is used in order to determine the sizes of the averaging area along different directions. The “averaging area” which gives us an idea of the obtained resolution can be approximated by an ellipse centered at a point, with axes equal to the largest \( S_{\text{max}}(x,y) \) and to the smallest \( S_{\text{min}}(x,y) \) values of \( S(x,y) \). The smallest \( S_{\text{min}}(x,y) \) and largest \( S_{\text{max}}(x,y) \) axes of the ellipse are calculated, and the resolution in each point is given by a single number, which is the mean size of the averaging area \( L = (S_{\text{min}}(x,y) + S_{\text{max}}(x,y))/2 \). As the resolution is closely correlated to the density of the crossing ray paths in each cell, it is clear that small values of the mean size of the averaging area (corresponding to high resolution) should appear in the areas that are crossed by a large number of ray paths and vice versa.

The second parameter is the stretching of the averaging area, which provides information on the azimuthal distribution of the ray paths and is given by the ratio

\[
2[S_{\text{min}}(x,y) - S_{\text{max}}(x,y)] / [S_{\text{min}}(x,y) + S_{\text{max}}(x,y)],
\]

Small values of the stretching parameter imply that the paths are more or less, uniformly distributed along all directions; hence the resolution at each point can be represented by the mean size of the averaging area. On the contrary, large values of this parameter (usually > 1) mean that the paths have a preferred orientation and that the resolution along this preferential direction is likely to be quite small (Yanovskaya, 1997).

The resolution length of our tomographic results is of the order of 50 km in most of the study region, but worsens near to the borders of the region where the path coverage is poor (Fig. 5).
stretching parameter of the averaging area (Fig. 6) is generally smaller than one and indicates that the azimuthal distribution of the paths is sufficiently uniform and that the resolution is almost the same along any direction.

In general, the estimations of the resolution obtained from the mean size of the area and the checkerboard test indicate that it is reasonable to divide the study region into 0.25°×0.25° cells and that the anomalies with a surface extension of about 25×25 km² or larger are reliable.

RESULTS AND DISCUSSION
Using the tomographic method, as described in the previous section, Rayleigh wave group velocity maps at 4.5s, 12s, 20s and 28s have been produced (Fig. 9). Surface waves of different periods are sensitive to seismic shear wave speeds at different depths, with the longer period waves exhibiting sensitivity to greater depths (see Fig. 8). Group velocity maps at different periods characterize shear wave velocity structure at different depths. In order to guide the interpretation, the partial derivatives of Rayleigh wave group velocity with respect to shear wave velocity are calculated. The partial derivatives are computed analytically (Urban et al., 1993) for the AK135 model but with the crust replaced by a model based on DSS data gathered in North-China. In figure 8 we have plotted the partial derivatives which reflect the sensitivity of the group velocity on the shear wave velocity versus depth for periods of 4.5s, 12s, 20s and 28s.

Group velocity maps at the four chosen periods are discussed here.

At 4.5s, the shortest period of our tomography results, the partial derivative shows a peak at a depth of about 7 km. The group velocity map at 4.5s is therefore sensitive to variations of shear wave velocity at depths around 7 km and mainly reveals the characteristics of the uppermost crust, and, in fact, it can be correlated with the sedimentary cover thickness. The boundary between NCB and the surrounding mountain ranges is clearly outlined. A broad low velocity zone is observed at NCB, which is due to the large thickness of sediments. Taihangshan and Yanshan uplifts are imaged as high velocity zones. The Quaternary intermountain basins, such as Yanqing-Huailai, Yangyuan-Yuxian, Datong and Zhangjiakou show up as low-velocity anomalies. A small low velocity anomaly is observed between Fuping and Yuxian, which is consistent with the location of the Lingshi basin. In general, the group velocity map correlates very well with known geological structures. The resolution in the southeastern part (NCB) is relatively low because the local noise in this part is very strong and at the same time wave attenuation in the sediment basin is very strong, thus it is very difficult to obtain cross correlations with high SNR.

At 12s period, the resolution is improved by the increase of ray-paths and the group velocity map shows lateral variations as large as 1.2 km/s. Geologic units with small areas can be identified clearly and Jizhong depression, Cangxian Uplift and Huanghua depression are mapped
as well. Affected by the thickness of sedimentary deposits, Jizhong depression and Huanghua depression are mapped with low velocities, while Cangxian uplift is mapped with high velocities.

The distribution of group velocity for a given period maps the average velocity structure over a certain depth range, as can be seen from Fig. 8. Taihangshan and Yanshan uplifts are mapped as high velocity anomalies. Yanqing-Huailai, Yangyuan-Yuxian and Datong basins still show up as low velocity anomalies. The distribution of the sediment layer in North-China controls the lateral variation of group velocity at 12s period. The distribution and strength of the low velocity anomaly reveal the relative thickness of the sediment layer. The DSS data and some other results reveal that the thicknesses of the sediment deposits in the Huanghua and Jizhong depressions are about 7-9 km and 6-10 km, respectively (Jia & Zhang, 2005; Editorial Group of “The 1976 Tangshan Earthquake”, 1982). Therefore the low velocity anomalies in the tomography maps at short period are an excellent indicator of the location and nature of the sedimentary basins in North-China, e.g. the extremely thick sedimentary deposit is the direct cause of the low velocity anomalies of Rayleigh wave in the Jizhong and Huanghua depressions.

Below the 20s period, the tomography maps dominantly reflect low velocity anomalies caused by sedimentary basins. Almost all the basins are mapped as low velocity anomalies. Compared to what can be seen at shorter periods, the area of low velocity anomaly in the Jizhong depression is smaller, while the high velocity anomaly in the Cangxian uplift is larger; the velocity contrast between the sediment basin, such as Yangyuan-Yuxian and Yanqing-Huailai Basins, and its surrounding areas decreases.

At 28s period, waves are primarily sensitive to depths between 30 and 50 km; namely, the lower crust velocity, the crust thickness and the uppermost mantle velocity. In this map the influence of the sediment basins decreases, with respect to what can be seen at shorter periods. The group velocity map at this period differs greatly from those obtained at 4.5s, 12s, 20s. High velocity anomalies are observed in the eastern part of the study region, while low velocity anomalies are observed in the northwest part. Thick crust tends to appear as low velocity anomalies and thin crust as fast anomalies on the map. Reflection and refraction profiles in North-China (Jia & Zhang, 2005) show that the crust is relatively thin in NCB, while it is thick in the northwest part of our study region: the crust thickness is about 28-29 km in Bohai Bay, about 35-36 km in Beijing and more than 40 km to the west of Taihangshan fault.

As one could expect from earlier studies, in the 28s period map, a well-defined low velocity zone is observed in the Beijing-Tianjin-Tangshan region. In fact, Zhu & Zeng (1990) find a low velocity region in the Beijing-Tianjin-Tangshan region at 50 km of depth, which extends to 100 km of depth beneath Tangshan and Tianjin, and, using regional seismic arrival data and Simultaneous Iterative Reconstruction Technique, Ding & Zeng (1994) reveal that a clear low velocity zone lies between Beijing and Tangshan in the 20-35 km depth range. Recent body wave
tomography shows a low velocity zone in the lower crust beneath the Beijing-Tianjin-Tangshan region (Huang & Zhao, 2004) as well.

From the tomography maps two further important features can be seen: (a) a high velocity zone near Datong, Shouzhou and Qingshuihe and (b) strong velocity gradient near the boundary between North-China basin and Yanshan-Taihangshan uplift. The zone with high velocity Rayleigh wave near Datong, Shouzhou and Qingshuihe is located at the northeastern margin of the Ordos block that shares the typical features of cratonic lithosphere and hasn't been affected by the NCC re-activation. The block is characterized by low seismicity, low heat flow, positive vertical velocity gradient and lack of active fault and magmatic activity (Qiu et al, 2005). The trend of the strong velocity gradients seen near the boundary of the North-China basin and the Yanshan-Taihangshan uplift is nearly identical to that visible in the Bouguer gravity anomaly map (Fig. 10), where, along the NE-SW-trending Taihangshan uplift, a continuous gradient zone is outstanding. The Taihangshan fault is within this gradient belt and P-wave tomography has shown that the fault cuts through the Moho interface and penetrates into the upper mantle (Huang & Zhao, 2004, Zhang et al, 2007). The belt represents a major lithospheric boundary and separates the NCC into western and eastern sectors, which can be shown to have fundamentally different architectures. Gravity anomaly values decrease from east to west and this indicates that the main density interface (Moho discontinuity) is deeper in the west. Thus both densities and velocity structures differ greatly on both sides of the Taihangshan fault.

North China has a long history of civilization and has the most detailed historical earthquake catalogue in China. Although we do not know the focal depths of the historic strong earthquakes, a statistical analysis of the modern seismicity suggests that most of the earthquakes occur in the middle crust in North China, mainly in the 10-20 km depth range (Zang & Yang, 1984; Yang et al., 1989). In order to analyze the relation between seismicity and lateral variations of group velocity at selected periods, we compute the velocity gradients of the group velocity maps at 9s, 10s, 11s and 12s, using 0.25°×0.25° cells, and compare them to the space distribution of all the large historic earthquakes (M≥6.0) which occurred in this region since 780 BC (The Earthquake Disaster Prevention Department of China Earthquake Administration, 1995, 1999; China Earthquake Networks Center, 2008). The histograms of the velocity gradient with respect to the earthquake number is shown in Fig. 11. If the velocity gradients are grouped into three intervals: <0.05 km/s, 0.05-0.15 km/s, >0.15 km/s, we find that most of the large earthquakes (about two-thirds) occurred in regions with moderate velocity gradients. Since the group velocity map at a given period cannot be easily related to a certain depth, a more rigorous interpretation of the relations between surface wave dispersion maps and seismicity must await a non-linear (e.g. Panza, 1981) 3-D inversion of the dispersion data, which is beyond the purpose of this paper.
CONCLUSIONS

Rayleigh wave Green functions between pairs of stations across North China are extracted from cross-correlations computed using 14 months of ambient noise data recorded from January, 2007 to February, 2008 at 200 temporary stations in North China. Group velocity maps at 4.5s, 12s, 20s and 28s periods are obtained by surface wave tomography. The resolution across most of the study area is comparable with the average interstation spacing (~35 km). To the authors' knowledge, the resolution presented here is the highest one in the China mainland to date. These high resolution maps provide new information on the complex structure and seismotectonics in North China and the group velocity anomalies are well-correlated with known geological features.

Rayleigh wave group velocity tomographic maps show strong anomalies correlated with NCB, Yanshan and Taihangshan uplifts, Yanqing-Huailai, Yangyuan-Yuxian and Datong basins, and the eastern margin of Ordos block. At the shortest periods, the velocity images map quite well the surface geology and the main topographic features: the basin and depression areas show up as low-velocity anomalies, while the uplift and mountainous areas are imaged as high-velocity zones. The trend of the velocity anomalies is well consistent with the trend of regional tectonics. The group velocity contours at 4.5s, 12s and 20s are consistent with the Bouguer gravity anomaly map in the Taihangshan fault area, therefore it is natural to formulate the hypothesis that the Taihangshan fault cuts, at least, through the entire crust. Most of the historical strong earthquakes (M≥6.0) are located at zones where the horizontal velocity gradient of group velocity, at the selected periods, is moderate.

The technique produces Rayleigh wave group velocity maps within North China with a resolution much higher than what can be obtained using earthquakes, even if high local noise and poor path coverage in NCB limit the resolution in this region.

ACKNOWLEDGMENTS

We thank T. B. Yanovskaya for providing the surface wave tomography code. We are grateful to the colleagues of Institute of Geophysics, China Earthquake Administration for their help in deploying the seismic stations, collecting and pre-processing the data. This work is supported by the National Natural Science Foundation of China (Grants No. 40774038), Basic Research Project of Ministry of Science & Technology China (Grants No. 2006FY110100), Special Fund on Fundamental Scientific Research for National Commonweal Scientific Research Institutions (Grant No. DQJB06A02). This work is also supported by Italian MUR and University of Trieste in the framework of the Internationalization PhD Program (2004-2006): Advanced methodologies in the field of geophysics and geodynamics (Prot. II04A1CHC8) Coordinated by Giuliano F. Panza.
REFERENCES


Figure 1. Topography and tectonic sketch map of the study region. Modified from Wang et al. (1989) and Deng et al. (2004). The legend is shown at the bottom. (1) Major faults. (2) Deduced faults. (3) Boundary of Cenozoic basins. (4) Depression areas in North China basin. The names of major faults and geological units are as following: 1, Taihangshan fault; 2, Wutaishan fault; 3, Yuxian-Yanqing fault; 4, Kouquan fault; 5, Nankou-Sunhe fault; 6, Xiadian-Fengheying fault; 7, Luanxian-Leting fault; 8, Changli-Ninghe fault; 9, Cangxian fault; 10, Cangxian uplift; 11, Chengning uplift; 12, Jizhong depression; 13, Huanghua depression; 14, Jiyang depression; 15, Linqing depression. The names of the basin are: A, Yanqing-Huailai Basin; B, Yangyuan-Yuxian Basin; C, Datong Basin. The inset map shows the location of North China.

Figure 2. Bandpass filtered (10-50s) cross correlations as a function of distance and lag time. The cross correlation is time reversed if the amplitude of the negative component is smaller than the amplitude of the positive one.
Figure 3. Example of dispersion measurement. (a) 14-month cross-correlation obtained between stations GUY and CHL. (b) FTAN diagram obtained after multiple filter analysis.

Figure 4. Distribution of seismic stations and inter-station raypaths at 12s period. The triangles and circles show the location of broadband and very broadband stations, respectively.
Figure 5. Resolution length (in km) for the study area.
Figure 6. Distribution of the elongation of the averaging area for the study region.

Figure 7. The initial (before tomography) and final (after tomography) group traveltime residuals for the four considered periods. The r.m.s. of the final residuals at each period is indicated on the panel.
Figure 8. Analytical partial derivatives (Urban et al., 1993) of the group velocity of Rayleigh wave (right), computed with respect to shear wave velocity (left), at 4.5s, 12s, 20s and 28s. For each layer the partial derivative is normalized with respect to the layer thickness.

Figure 9. Rayleigh wave group velocity map at different periods and the epicenters (white circles) of large historical and recent earthquakes with $M \geq 6.0$; the diameters of the circle are proportional to the magnitude of the earthquake.
Figure 10. Bouguer gravity anomaly map in mGal. Modified from Yin et al. (1989).

Figure 11. Histograms of the number of large earthquakes with respect to group velocity gradients at 9s, 10, 11s and 12s.