The updated crustal attenuation in North China using M_L amplitude tomography*

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Abstract We have updated the lateral variations of the quality factor Q_0 (Q at 1 Hz) beneath the crust of North China using M_L amplitude tomography with near three times data. The data were selected from the Annual Bulletin of Chinese Earthquakes (ABCE) in 1985–2009, including 26 283 M_L amplitude readings from 4 204 events recorded by 38 stations. The result is similar with previous research but has higher resolution. Estimated Q_0 values are consistent with tectonic and topographic structure in North China. Q_0 is low in the active tectonic regions having many faults, such as Bohai bay, North China basin, the Shanxi and Yinchuan grabens, while it is high in the stable Ordos craton. Q_0 values are low in several topographically low-lying areas, such as the North China, Taikang-Hefei, and Subei-Huanghai Sea basins, whereas it is high in mountainous and uplift regions exhibiting surface expressions of crystalline basement rocks: the Yinshan, Yanshan, Taihang, Qinling and Dabie mountains, Luxi and Jiaoliao uplifts. Quality factor estimates are also consistent with Pn and Sn velocity patterns. High velocity values in general correspond with high Q_0 and vice versa. This coincides with a common temperature influence in the crust and uppermost mantle.

Key words: amplitude tomography; Q value; North China

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1 Introduction

North China craton is a re-active subplate with thinning of the lithosphere since Cenozoic, and with strong intraplate seismicity. The tectonics of North China craton, including Ordos block and North China basin is expressed by the development of large-scale strike-slip faults, rifts, volcanic fields, and large intraplate earthquakes. These features maybe resulted from Indo-Asian collision and/or subduction of the western Pacific (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Northrup et al., 1995; Zhang et al., 2003; Liu et al., 2004c), and show large deformation in crust. Further detail structure of crust is necessary to understand well the geodynamic origin of North China craton. In this paper, the updated attenuation structure of crust

beneath North China has been obtained using M_L amplitude tomography with near three times data.

The M_L amplitude tomography had been proposed by Pei et al. (2006) and applied successfully in China (Wang et al., 2007, 2008; Ma et al., 2007; Hearn et al., 2008; Pei et al., 2010) and Japan (Pei et al., 2009), and it can also be applied for M_S amplitude data (Hearn et al., 2009). This amplitude tomography can reach the same resolution as seismic travel-time tomography methods because of the same quantity order of data set between travel-time and amplitude data from regional event bulletins. There are very large quantity amplitude data set in the ABCE (Annual Bulletin of Chinese Earthquakes) compiled by Institute of Geophysics of China Earthquake Administration (IGCEA), including not only M_L , but also m_b , m_B and M_S amplitudes. Over 100 stations of the Chinese seismic network have been routinely reporting amplitudes for over a decade. These data provide consistent magnitude information, which is valuable for studying regional variations in seismic attenuation.

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A large body of research focused on attenuation in North China and surrounding regions using waveforms. Surface waves are often inverted for attenuation (e.g., Romanowicz, 1995; Li et al., 2000; Hong et al., 2003; Gung and Romanowicz, 2004; Jemberie and Mitchell, 2004). Lg wave data have also been applied to attenuation tomography (e.g., Mitchell et al., 1997; Phillips et al., 2000, 2001, 2005a; Cong et al., 2003; Taylor et al., 2003; Liu et al., 2004a, b). Tomographic inversion for regional imaging of Q has been performed in earlier studies using limited waveform data sets (e.g., Haberland and Rietbrock, 2001; Liu et al., 2004b; Phillips et al., 2005a). These researches show low resolution because of small data set in a large area. In this paper, we present a study of tomographic attenuation with higher resolution in North China using a large set of amplitude data which were measured originally to calculate M_L magnitude of local and near regional events.

2 Data

We used the M_L amplitude data of North China from ABCE between 1985 and 2009. Most of the data are from seismograms recorded on short-period DD-1 seismographs, whose amplitude response has a frequency band of 0.5 to 20 Hz. At each station, the maximum amplitudes come from the average of the two components with the error less than 10%. The data were selected using the following criteria: each event was recorded by at least two stations; each station recorded at least five events; the reported period of the S-wave at maximum amplitude is between 0.2 s and 1.3 s; epicentral distance is between 200 km and 900 km and event depth is less than 30 km. We finally obtained 26 283 M_L amplitude readings from 4 204 events recorded by 38 stations, as shown in Figure 1. It is near three times more data than 10 899 in previous research (Pei et al., 2006) within a smaller area.

Figure 1 Distribution of ray paths, stations (triangles) and events (crosses). The lines represent rays from events to stations. We obtained 26 283 M_L amplitude readings from 4 204 events recorded by 38 stations.

These M_L amplitudes are the maximum amplitudes measured on the horizontal components of short-period instruments and are used for ray paths less than 1 000 km in length. They are generally measured within the wavetrain that corresponds to the short-period Sg wave for short distance. At longer distances this is coincident with the longer period Lg wavetrain. In general, the amplitude of Lg should be maximum for distance larger than 200 km. So we selected the data with distance larger than 200 km and Lg waves travel within the crustal waveguide and are thus sensitive to crustal variations in attenuation. Thus, the attenuation we obtained results from whole crust structure.

3 Method

The attenuation of seismic waves between station i and source j can be estimated from the amplitude spectrum $A_{ij}(f)$, where f is the frequency at which the amplitude is measured. Amplitude is influenced by several factors such as the size of the event, station site and instrument gain, geometrical spreading, and seismic attenuation. With these, the total amplitude can be written as (e.g., Sanders, 1993; Haberland and Rietbrock, 2001):

$$A_{ij}(f) = O_j(f)S_i(f)G_{ij}(R)B_{ij}(f, R), \quad (1)$$

where $O_j(f)$ represents the event amplitude at frequency f , $S_i(f)$ is the site and instrument gain, $G_{ij}(R)$ is the geometrical spreading factor at distance R , and $B_{ij}(f, R)$ is seismic attenuation. The event radiation pattern has not been included. However, the maximum amplitude for S-wave is produced by the interference of guided waves originating from many different sectors of the focal sphere, which tends to reduce the effect of the radiation pattern. This is reflected in the relative consistency of M_L magnitude estimates at different seismic stations for the same event. We include frequency dependence in all terms except geometrical spreading.

The attenuation of S waves, $B_{ij}(f, R)$, is attributed to the quality factor Q . We assume a frequency dependent Q and model it as an exponential decay (e.g., Sanders, 1993; Haberland and Rietbrock, 2001):

$$B_{ij}(f, R) = \exp\left(-\frac{\pi f R}{vQ}\right) = \exp(-cRQ_0^{-1}), \quad (2)$$

where $c = \pi f^{1-\eta}/v$, $Q = Q_0 f^\eta$, v is S-wave velocity, Q_0 and η are the S-wave Q at 1 Hz and its power-law frequency dependence, respectively. Using equation (2) and taking the natural logarithm of equation (1) yields

$$Y_{ij} = \ln A_{ij}(f) - \ln G_{ij}(R) = a_i + b_j - Q_0^{-1}cR, \quad (3)$$

where the station term is $a = \ln S_i(f)$ and event term is $b_j = \ln O_j(f)$. We use a frequency dependent source spectrum $O(f)$ (Brune, 1970; Hanks and Wyss, 1972) that can be described by a long-period spectral level Ω_0 and the corner frequency f_c as $O(f) = \Omega_0/(1 + (f^2/f_c^2))$. It is approximately linear to M_L magnitude and $\lg O(f) = -1.676 + 1.202M_L$ (Wang et al., 2007). So the effect of magnitude will be removed using this relation between $O(f)$ and M_L in equation (3). The site response, $S_i(f)$, includes the effect of instrument gain and site amplification. The spectral dependence of $S_i(f)$ is unknown, however, the M_L bandwidth is small (0.5 Hz to 2 Hz) and the instrument response is reasonably flat within this range. We therefore assume $S_i(f)$ is also independent of frequency.

The geometrical spreading (Castro et al., 1996), $G(R)$, is considered to be proportional to $(1/R)^k$, where k is the geometrical spreading coefficient, which chiefly depends on wave type. $k=1.0$ implies spherical spreading of body waves and $k=0.5$ represents cylindrical spreading of surface waves. For Lg wave, the theory spreading is very near to 1.0 (Yang, 2002). The amplitude data we selected mostly come from Lg wave, so we take $k=1.0$, $v=3.3$ km/s in our inversion.

Q_0 and η need knowing before inversion. We fit equation (3) for each period from 0.2 s to 1.3 s to obtain Q at different frequency, and then fit $Q = Q_0 f^\eta$ under logarithm coordinate to get Q_0 and η .

Equation (3) is very similar to the Pn travel time equation (Hearn and Ni, 1994; Pei et al., 2007), thereby allowing us to resolve lateral variation of Q_0 using the Pn tomography method. We first estimate the average model by fitting the line $Y-cR$. If we discretize the crust into small 2D cubes of X km by Y km, then equation (3) can be rewritten as

$$Y_{ij} = a_i + b_j - \sum_k Q_{0k}^{-1} c R_{ijk}.$$

By subtracting Y_{ij} from the average model (fitted line), a perturbation equation can be determined as follows:

$$\Delta Y_{ij} = \Delta a_i + \Delta b_j - \sum_k \Delta Q_{0k}^{-1} c R_{ijk}, \quad (4)$$

where ΔY_{ij} is the amplitude residual; ΔQ_0 , Δa_i and Δb_j are perturbation of quality factor, station term and event term, respectively. Equation (4) can be recast as $A\mathbf{x} = \mathbf{d}$, where $\mathbf{d}$ is the data vector, $\mathbf{x}$ is the vector of unknowns and A represents the model parameters. We apply

damped LSQR (Paige and Saunders, 1982) with preconditioning to find the least-squares solution. Laplacian smoothing was applied in the inversion (Lees and Crosson, 1989).

4 Results

We fit equation (3) for each period from 0.2 s to 1.3 s to obtain Q at different frequency, and then fit $Q=Q_0f^\eta$ under logarithm coordinate to get $Q_0=315$ and $\eta=0.94$ (Figure 2). The Q_0 is smaller than 415 in previous research (Pei et al., 2006) because of different rays coverage and different magnitude correction. That more rays cross the high attenuation area such as rifts and North China basin will result in lower average Q_0 . Different parameter η and magnitude correction also cause different Q_0 . In this paper, the parameter and magnitude correction are more reasonable. We discretize the crust into blocks with cell dimensions of $15'\times 15'$, and adopt a damping constant of 500. The Q_0 lateral variations, the station term and the event term perturbations are ob-

tained by tomographic inversion of the M_L amplitude residuals after 60 iterations. Figure 3 shows the resulting

Figure 2 The relation between Q value and their period T (or frequency) and fitting line.

Figure 3 Imaged Q_0 lateral variations. Blue corresponds to a high value and red to low. The thin black lines indicate active faults (Zhang et al., 2003a). Magenta circles represent earthquakes with magnitudes greater than 7.0 (Wang et al., 2003).

lateral variations of the quality factor Q_0 , which varies from 115 to 515. Blue corresponds to a high quality factor (low attenuation) and red corresponds to a low quality factor (highly attenuative crust).

The residuals between -2 and $+2$ are used in the tomographic inversion. The standard deviation of the residuals for the original data is 0.71, and is reduced from 0.68 for the selected data to 0.46 after the inversion (Figure 4). Checkerboard tests were employed to analyze the spatial resolution of our solution. For the given ray paths in this study, theoretical amplitude residuals were calculated for input ΔQ_0 models with ± 200 in different square sizes. Gaussian random noise with zero

mean and a standard deviation of 0.46 was added to the calculated residuals. Then the synthetic amplitude residuals were inverted to determine whether the squares could be resolved. Figures 5 shows checkerboard test models with cell size of 1° by 1° . The tests indicate that tomogram resolution is on the order of 1° in most regions and improved largely than 2° in previous research (Pei et al., 2006); however the result is very similar. Random error of 0.46 can be damped and reduced in the checkerboard test indicates that the amplitude data errors of 10% have little influence on the resultant Q values.

Figure 4 Distribution of amplitude residuals versus reduced epicentral distance (cR) before inversion (top) and after inversion (bottom). Residuals between -2 and $+2$ are used in the tomographic inversion. The standard deviation of the residuals is reduced from 0.68 to 0.46 after inversion. The gray lines are histograms with 0.2 s residuals of the bin width, for residuals of original data (top) and residuals after inversion (bottom), respectively.

5 Discussion and conclusions

Figure 3 shows that the quality factor is consistent with the tectonic structure in North China. Q_0 is low in the active tectonic area with many faults, such as Bohai bay, North China basin, the Shanxi and Yinchuan graben; while Q_0 is high in the stable Ordos craton. This elevated attenuation can be attributed to the greater scattering and/or absorption in the fractured or faulted zone, compared to intact rocks. At the same time, the Q_0

is consistent with topography in East China. Q_0 is low in some large basins such as the North China basin, Taikang-Hefei basin, and Subei-Huanghai Sea basin. High Q_0 occurs in most mountains and uplift regions where crystalline basement appears at the surface, including the Yinshan, Yanshan, Taihang, Qinling and Dabie mountains, Luxi and Jiaoliao uplifts. But there is a high attenuation zone cutting through Yinshan mountain. Oil and/or gas were found in all basins mentioned above, and Mesozoic and older rocks are ubiquitous in

the mountainous areas and uplift regions mentioned (Ma, 1989; Steinshouer et al., 1999). Low Q_0 observed in the basins may result from fluid-filled cracks and pores in the upper crust and deep sedimentary basins.

Temperature may also be an important factor in the Q_0 pattern since the Earth's heat flow is high in basins and low in mountains and uplift regions in eastern China (Hu et al., 2001; Wang et al., 2003).

Figure 5 The resolution image created from a checkerboard test model with cell sizes of 1° by 1° . As for the checkerboard test model, Gaussian noise was added with standard deviation 0.46. The test indicates that tomogram resolution is on the order of 1° in most regions.

High attenuation values in the North China basin were observed by Liu et al. (2004b) and Phillips et al. (2005). Our results are consistent with these earlier studies, but provide higher resolution and more detailed information in the North China basin, Shanxi and Yinchuan grabens, Ordos craton and surrounding regions.

Our estimate of the quality factor is also consistent with previously determined patterns of Pn (Wang et al., 2003; Hearn et al., 2004; Liang et al., 2004; Sun et al., 2004, 2006; Phillips et al., 2005b; Sun and Toksöz, 2006) and Sn velocities (Pei et al., 2004; Sun et al., 2008). High velocity almost always corresponds to high Q_0 and low velocity to low Q_0 , possibly because of the influence of common temperature in the crust and uppermost

mantle.

In summary, this study uses tomographic imaging to update crustal attenuation beneath North China craton using much more amplitude data. (1) We find that attenuation levels are correlated with regional tectonic structure. High attenuation often occurs in active tectonic areas with significant faulting, while attenuation is low in the stable Ordos craton. (2) The estimate of attenuation shows a close correlation with topography. Q_0 is generally low in basins, whereas high Q_0 mostly occurs in mountains and uplift regions where crystalline basement appears in the surface. It is possible that low Q_0 in basins is caused by fluid in the upper crust, high heat flow and deep sediment in basins, while high Q_0 in the mountains and uplift regions results from the pres-

ence of old, dense rocks and low heat flow. (3) Quality factor is also consistent with Pn and Sn velocity patterns. High velocity generally corresponds with high Q_0 and low velocity with low Q_0 , possibly because of a common temperature influence in the crust and uppermost mantle.

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