Seismic image and origin of the Changbai intraplate volcano in East Asia: Role of big mantle wedge above the stagnant Pacific slab

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ABSTRACT

We determined P-wave tomography of the crust and upper mantle under the Changbai volcanic area in Northeast Asia by using 289,318 arrival-time data from 4802 local earthquakes and 9599 teleseismic events. A prominent low-velocity anomaly is clearly imaged in the crust and upper mantle down to about 410 km depth beneath the Changbai volcano. A broad high-velocity anomaly is revealed in the mantle transition zone and deep earthquakes occurred actively there, suggesting that the subducting Pacific slab is stagnant in the mantle transition zone under East Asia. Our results suggest that the formation of the Changbai and other intraplate volcanoes in Northeast Asia is related to the upwelling of hot and wet asthenospheric materials in the big mantle wedge above the stagnant Pacific slab. Hence the active intraplate volcanoes in Northeast Asia are not hotspots related to deep mantle plumes but are caused by plate tectonic processes in the upper mantle.

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1. Introduction

In the East Asia continent there are many Cenozoic volcanoes, but only a few are still active now, such as the Changbai and Wudalianchi volcanoes in Northeast (NE) China and Tengchong volcano in Southwest China (Liu, 1999; Liu, 2000) (Fig. 1). The three active volcanoes have erupted many times in the history. For example, the Changbai volcano erupted six times in BC 1120, AD 1050, 1413, 1597, 1668, and 1702 (Simkin and Siebert, 1994), the Wudalianchi volcano erupted during 1719–1721 (Liu, 2000), and the Tengchong volcano erupted during 1719–1721 (Liu, 2000), and the Tengchong volcano erupted during 1465–1620 (Liu, 2000). Although many studies have been made by using various approaches, the origins of these intraplate volcanoes in East Asia are still not very clear.

The Changbai intraplate volcano is located close to the boundary between China and Korea (Fig. 1). It is also called Tianchi or Baiton-shan volcano. In recent years many researchers have used multidisciplinary approaches to investigate the crust and upper-mantle structure of the Changbai volcano. For example, magnetotelluric soundings detected a high-conductivity layer in the crust under the volcano (Tang et al., 2001); seismic explosion studies revealed low-velocity (low-V) anomalies in the crust and uppermost mantle under the volcano, which are considered to reflect magma chambers (Zhang et al., 2002). Some researchers considered the Changbai volcano as a hotspot like Hawaii (e.g., Turcotte and Schubert, 1982), while others suggested that its formation was associated with the subduction of the Pacific plate, upwelling of the hot asthenospheric materials, and lithospheric fractures (e.g., Tatsumi et al., 1990).

Because of the lack of digital seismic stations in NE Asia, the seismic structure of the crust and mantle under this region had not been determined till the very recent time. A portable seismic network consisting of 19 stations was installed in the Changbai volcanic area from June 1998 to April 1999, which recorded seismic waves from some distant earthquakes (Wu and Hetland, 1999). The waveform data were used to estimate the depth distribution of the Moho, 410 and 660 km discontinuities under the Changbai area with teleseismic receiver-function methods (Ai et al., 2003; Li and Yuan, 2003; Hetland et al., 2004). Zhao et al. (2004) and Lei and Zhao (2005) collected 548 high-quality P-wave arrival times from 68 teleseismic events recorded by the 19 portable stations and three permanent stations (Mudanjiang, Beijing, and Hailaer) which belong to the Chinese Digital Seismic Network (CDSN), and used the data to determine the first 3-D P-wave velocity structure of the upper mantle under the Changbai volcano. Their results show a prominent low-V zone down to about 400-km depth under the Changbai volcano and a high-velocity (high-V) anomaly in the mantle transition zone. However, the previous tomographic images (Zhao et al., 2004; Lei and Zhao, 2005)...
have a low resolution because of the small data set used in those studies.

In the present work we have determined a high-resolution 3-D P-wave velocity structure down to 650 km depth under the Changbai volcano by using simultaneously a great number of arrival-time data from local and regional earthquakes and teleseismic events recorded by many permanent and portable seismic stations in and around Changbai. Our present results shed new light on the deep structure and origin of the Changbai intraplate volcano and mantle dynamics under East Asia.

2. Data and method

In this work we used 645 analog and digital seismic stations of the Chinese Seismic Network and 19 portable seismic stations deployed by Wu and Hetland (1999) (Figs. 2a and 3). The 19 portable
Fig. 3. (a) Map showing the surface topography of East Asia. The box shows the location of the present study area enlarged in (b). The three triangles show the intraplate volcanoes in China (from north to south: Wudalianchi, Changbai, and Tengchong). (b) Tectonic background around the Changbai volcano (the red triangle). Solid lines show the major active faults. Black and yellow triangles denote the permanent and portable seismic stations, respectively.

Fig. 4. Epicenter locations of the 9599 teleseismic events (star symbols) used in this study. The concentric circles show the distances (30, 60 and 90°) from the center of the study area.

Fig. 5. One-dimensional P-wave velocity model used in this study (grey lines) which is modified slightly from the IASP91 Earth model (dashed lines).
stations were located around the Changbai volcano (Fig. 3), while most of the permanent seismic stations are located west of Changbai and there are no stations on the Korea Peninsula and Japan Sea. However, the use of data from many teleseismic events in the eastern hemisphere (Fig. 4) recorded by the portable and permanent stations has provided crisscrossing seismic rays in the upper mantle under the Changbai volcano.

We collected 49,799 arrival times from 4802 local and regional earthquakes occurred during 1980–2005 (Fig. 2b), and 239,519 arrival times from 9599 teleseismic events occurred during 1980–2002 (Fig. 4). The picking accuracy of the arrival times is estimated to be 0.1–0.2 s. The 548 teleseismic data recorded by 22 stations in the Changbai area measured by Zhao et al. (2004) and Lei and Zhao (2005) are also used in this study.

To analyze the arrival-time data, we used the tomographic method of Zhao et al. (1994, 2004) to combine the teleseismic relative residuals with local and regional earthquake arrival times in the tomographic inversion. The local and regional earthquakes are relocated in the inversion process. Hypocenter parameters of the teleseismic events determined by Dr. E.R. Engdahl with a procedure described by Engdahl et al. (1998) are used in this study and they are fixed in the inversion process because relative teleseismic residuals are used (see Zhao et al., 1994, 2006). The 1-D starting model (Fig. 5) for the 3-D tomographic inversion is derived from the iasp91 Earth model (Kennett and Engdahl, 1991) with slight changes in the crust and uppermost mantle according to a previous tomographic study for East Asia (Huang and Zhao, 2006). A 3-D grid is arranged in the modeling space. P-wave velocity perturbations at the grid nodes are taken as unknown parameters. The velocity perturbation at any point in the model is calculated by linearly interpolating the velocity perturbations at the eight grid nodes surrounding that point. A 3-D ray tracing method is used to calculate travel times and ray paths (Zhao et al., 1992; Zhao, 2004). The large and sparse system of observation equations is resolved by using a conjugate-gradient algorithm with damping and smoothing regulations (Zhao, 2004).

We conducted many inversions and synthetic tests with different grid intervals, and found that the optimal grid spacing is $0.8 \times 0.8^\circ$ in the horizontal direction and 20–80 km in depth. The total number of grid nodes in the model is 7488, but only the
Fig. 7. North-south (a) and east-west (b) vertical cross sections of P-wave velocity tomography along profiles shown in (c). Red and blue colors denote slow and fast velocity anomalies (in %) from the 1-D velocity model shown in Fig. 5. The velocity perturbation scale is shown beside (a). The black triangles denote the active Changbai volcano. The dashed lines show the 410-km discontinuity. (c) Map showing locations of the two cross sections in (a) and (b). The red triangle denotes the Changbai volcano. Black crosses and white dots show the shallow (0–30 km) and deep (450–600 km) earthquakes.

3. Results and resolution analyses

Figs. 6 and 7 show the final P-wave tomographic images in plan views and along two vertical cross sections beneath the Changbai volcano. The images are generally consistent with the previous results (Zhao et al., 2004; Lei and Zhao, 2005). A clear low-V anomaly is visible down to 410 km depth under the Changbai volcano. In the N–S vertical cross section (Fig. 7b) the low-V zone is confined right beneath the Changbai volcano, while it spreads toward the west and east in the asthenosphere (250–400 km depth) in the E–W cross section (Figs. 6 and 7a). A continuous high-V anomaly is clearly visible in the lower portion of the mantle transition zone, and deep earthquakes occurred within the high-V zone in the depth range of 480–600 km. Referring to the previous regional and global tomography results (Zhao, 2004; Lei and Zhao, 2005; Huang and Zhao, 2006), we believe that the high-V zone represents the stagnant Pacific slab in the transition zone. A significant difference between the present result and the previous ones is that the stagnant Pacific slab is about 100 km thick in our tomographic images (Fig. 7), while it was imaged as a high-V zone of about 200 km thick by the previous tomographic studies. This significant improvement in the imaging of the stagnant Pacific slab is due to the much better data set used in this work, which leads to the higher-resolution of our present tomography.

To confirm the main features of the tomographic result, we conducted extensive resolution analyses. Here we show the results of two synthetic tests. One is checkerboard resolution test (CRT), the other is a synthetic resolution test. In CRT, we assigned positive and negative velocity perturbations of ±3% alternately to the grid nodes and calculated travel times for this model to make synthetic data, and then we inverted the synthetic data. Fig. 8 shows the results of CRT along two profiles as shown in Fig. 7c. As a whole, the CRT results are very good and the checkerboard pattern is well recovered under the Changbai volcano down to 660 km depth, suggesting that the main features of the tomographic images under Changbai are reliable.

Fig. 9 shows the results of a synthetic test for assessing the reliability of the high and low velocity zones beneath the Changbai volcano along the two profiles shown in Fig. 7c. Unlike the CRT, the pattern in the synthetic test is not the alternative positive and negative velocity perturbations, but instead some main features appeared in the obtained tomographic result (Fig. 7). It is clear that the input velocity anomalies are generally well recovered, though there are some differences in the amplitude of velocity anomalies (Fig. 9). This proves the reliability of the low-V anomaly in the depth range of 0–410 km and the high-V zone in the mantle transition zone beneath the Changbai volcano.

4. Discussion

4.1. Other seismic evidence

Fig. 10 shows two vertical cross sections of whole-mantle P-wave tomography under the Changbai and Wudalianchi volcanoes from the global tomography model of Zhao (2004). About one million arrival times of first P-wave and later phases (pP, PP, PcP, and Pdiff waves) were used in the inversion, and depth variations of the velocity perturbations at 5987 grid nodes with hit count over 30 were resolved by inverting the 289,318 travel-time data.
Moho, 410 and 660 km discontinuities were also taken into account (for details, see Zhao, 2004). In the upper mantle, the subducting Pacific slab is imaged clearly and earthquakes occurred down to about 600 km depth within the slab (Fig. 10). Under East Asia, the Pacific slab becomes stagnant in the transition zone. Pieces of high-V anomalies are visible in the lower mantle under the stagnant slab, and they have piled up in the lowermost mantle (Fig. 10). Similar features were also found in other global tomographic models (e.g., Bijwaard et al., 1998).

We also estimated the stress regime in the subducting Pacific slab by using the Harvard CMT solutions of deep earthquakes under the Japan Sea and East Asia (Ekstrom et al., 2005). The result shows that the compressive stress axes of almost all deep earthquakes are nearly parallel with the down-dip direction of the slab (Fig. 11), indicating that the Pacific slab is under the compressive stress regime in the depth range of 200–600 km. This result is well consistent with the earlier findings by Isacks and Molnar (1971). We consider that such a stress regime in the slab is caused by the stagnant slab meeting strong resistance at the 660-km discontinuity, being consistent with the seismic tomography results (Figs. 7 and 10).

All these seismological results suggest that the subducting slab under NE Asia does not easily penetrate down to the lower mantle, but meets strong resistance when it encounters the 660-km discontinuity. The slab bends horizontally, and accumulates there for a long time (ca. 100–140 m.y.), and then finally collapses to fall down as blobs onto the core-mantle boundary as a result of very large gravitational instability from phase transitions (Maruyama, 1994; Mitrovica et al., 2000; Zhao, 2004). The receiver-function studies using the waveform data from the portable seismic network obtained similar results (Ai et al., 2003; Li and Yuan, 2003). Fig. 10 also shows that very slow anomalies exist in the upper mantle right beneath the Wudalianchi and Changbai volcanoes, right above the stagnant Pacific slab in the mantle transition zone. The global tomographic images (Fig. 10) are generally consistent with the regional tomography results (Fig. 7; Huang and Zhao, 2006). These results are also quite similar to the images under the Fiji-Tonga region where the back-arc volcanoes in Fiji and the Lau spreading center are located above very slow anomalies in the mantle wedge right above the subducting Tonga slab (Zhao et al., 1997; Conder and Wiens, 2006).

4.2. Big mantle wedge model

There are several types of volcanoes on Earth, such as the mid-ocean ridge volcanoes, subduction zone volcanoes, hotspots caused by deep mantle plumes, and intraplate volcanoes associated with upwelling of hot asthenospheric materials and lithospheric fractures (e.g., Tatsumi et al., 1990). Apparently, the Changbai and Wudalianchi volcanoes are not mid-ocean ridge volcanoes. Because the subducting Pacific slab is stagnant in the mantle transition zone under NE Asia, the volcanoes are not hotspot like Hawaii, Iceland, and Eifel (Ritter et al., 2001; Waite et al., 2006).

The regional and global tomographic images (Figs. 7 and 10) suggest that the Changbai and Wudalianchi volcanoes are a kind of back-arc intraplate volcanoes whose formations are closely related to the deep subduction of the Pacific slab and its stagnancy in the
mantle transition zone. The broad upper-mantle region above the stagnant Pacific slab may have formed a big mantle wedge (BMW) under the Japan Sea and NE China (Fig. 10). Slow velocity anomalies in the back-arc region are generally associated with the back-arc magmatism and volcanism caused by the deep dehydration process of the subducting slab and the convective circulation process of the mantle wedge (Zhao et al., 1994, 1997; Stern, 2002). These processes may have led to the large-scale upwelling of the hot asthenospheric

![Fig. 9](image1)

Results of a synthetic test for the velocity anomalies under the Changbai volcano along AB (a) and CD (b) profiles shown in Fig. 7c. The left panels show the input models, while the right panels show the output models resulting from the tomographic inversion. Black and white circles denote low and high velocities, respectively. The velocity perturbation scale is shown at the bottom. The triangles show the location of the Changbai volcano. The dashed lines show the 410-km discontinuity.

![Fig. 10](image2)

(a and b) Vertical cross sections of whole-mantle P-wave tomography (Zhao, 2004). Red and blue colors denote slow and fast velocity perturbations (in %), respectively, from the 1-D iasp91 Earth model. The velocity perturbation scale is shown below the cross sections. White dots denote earthquakes within 150-km width of the profiles. The two lines show the 410 and 660 km discontinuities. Solid triangles show the intraplate volcanoes. The reverse triangles show the location of the Japan Trench. (c) Map showing locations of the two cross sections in (a) and (b). Triangles denote hotspots or intraplate volcanoes on Earth.
Fig. 11. (a) Plan view and (b) east-west vertical cross section showing the distribution of compressive axis (P-axis) of deep earthquakes under the Japan Sea and East Asia. The red triangles denote active and Quaternary intraplate volcanoes. The vertical cross section is along line A–B shown in (a). The two dashed lines show the 410 and 660 km discontinuities.

Fig. 12. (a) Surface tectonic features in Northwest Pacific and Northeast Asia. Black patches denote the Cenozoic basalts. (A) Baikal rift; (B) Shanxi graben; (C) Tancheng-Lujiang fault zone; (D) Okinawa trough. (b) A schematic east-west vertical cross section showing the upper-mantle structure beneath Northeast Asia. The subducting Pacific slab becomes stagnant in the mantle transition zone. The convective circulation process in the big mantle wedge (BMW) and deep dehydration reactions of the subducting slab cause upwelling of hot and wet asthenospheric materials, leading to the formation of the continental rift systems as well as intraplate volcanoes in Northeast Asia (modified from Tatsumi et al., 1990 and Zhao et al., 2004).
materials under NE Asia and caused the continental rift systems and intraplate volcanism in the region. Because the very old (hence very cold) Pacific plate is subducting beneath East Asia at a rapid rate (7–10 cm/year), the dehydration reactions may not fully complete at the shallow depth (100–200 km) of the mantle. Hydrous Mg–Si minerals in the subducting Pacific slab may continue to release fluids through dehydration reactions at the depths of mantle transition zone (Inoue, 1994; Ohtani et al., 2004; Komabayashi et al., 2004).

Deep dehydration reactions of the rapidly subducting Pacific slab have also been found in the Tonga subduction zone (Zhao et al., 1997; Conder and Wiens, 2006).

Tatsumi et al. (1990) first invoked the asthenospheric injection to explain the formation of the Wudalianchi and Changbai volcanoes, but they did not consider the stagnant Pacific slab under the region because such a slab structure was unknown at that time. Here we modify their model to emphasize the roles of the stagnant Pacific slab and the big mantle wedge in the formation of the intraplate volcanism in East Asia (Fig. 12b). The extensional rift systems and faults widely existing in East Eurasia (Fig. 12a) may be the surface manifestation of a deep dynamic process such as deep subduction of the Pacific slab, upwelling of hot asthenospheric materials, lithospheric fractures and intracontinental rifting (e.g., Zhao et al., 2004, 2006). Recent results of S-wave splitting (Liu et al., 2008) and geochemical analysis (Chen et al., 2007; Zou et al., 2008) also support this BMW model. Zou et al. (2008) presented U-series data and trace element data which argue against the deep dehydration process and suggested that the piling up and thickening of the stagnant Pacific slab in the transition zone, together with the convective circulation process in the BMW, help drive the asthenosphere upwelling and induce decompression melting.

In this work we determined high-resolution tomographic images of the upper mantle under the active Changbai volcano, but such a detailed mantle tomography is still not yet available for the Wudalianchi volcano. Global tomographic images show that the large-scale structure under the Wudalianchi volcano is quite similar to that under the Changbai volcano (Fig. 10). Hence we consider that the two volcanoes have the same origin. To confirm this conjecture, it is necessary to install a dense seismic network of portable or permanent stations in the Wudalianchi area in the near future to determine a detailed 3-D structure of the crust and mantle under the volcano to clarify its origin.

Recently water content and geotherm of the upper mantle under NE China were estimated from the electrical conductivity and P-wave velocity under the region (Ichiki et al., 2006) (Fig. 13). It is found that in the deep part of the upper mantle (250–400 km depth), neither the dry pyrolite nor the dry harzburgite condition provide consistent electrical and seismic geotherms, while the discrepancy can be explained by allowing for a small amount of water (500–1000 ppm H/ Si) with the seismic geotherm. In the shallow mantle (<250 km depth), the electrical and seismic geotherms are consistent with each other within 1500–1700 °C under the dry harzburgite condition, but they are inconsistent by more than 100 °C under the dry pyrolite condition (Fig. 13b). Alternatively, the wet pyrolite condition applied to the deeper part of the upper mantle also satisfies the electrical conductivity and seismic structure in the shallow mantle (Fig. 13a). These results suggest that the entire upper mantle or at least the asthenosphere under NE Asia contains fluids, which is consistent with the tomographic results showing prominent low-velocity anomalies down to 410 km depth (Figs. 7 and 10). The wet upper mantle is possibly caused by the deep dehydration reactions of the stagnant Pacific slab that contains sufficient amount of hydrous minerals down to the transition zone depths (Shieh et al., 1998; Ohtani et al., 2004; Komabayashi et al., 2004).

Recent studies using GPS (global positioning system) observations indicate that not all the plate boundaries are narrow deformation zones as assumed by the theory of plate tectonics when it was first proposed (Stein and Freymueller, 2002). Some plate boundaries can be very broad deformation zones, for example, the continental collision between the Indian and Eurasian plates has resulted in the Tibetan plateau of a few thousands kilometers wide. The Changbai and Wudalianchi volcanoes are located in the interior of the Eastern Asia continent, leaving the Japan Trench farther than 1000 km (Fig. 1). The present and previous tomographic images show that the subducting Pacific slab is stagnant in the mantle transition zone under NE Asia, and it has greatly affected the intraplate seismic and volcanic activities in NE China (Zhao, 2004; Huang and Zhao, 2006). These results suggest that the western Pacific plate boundary is a deformation zone as broad as over 1000 km wide, and the subduction of the Pacific plate has far-reaching effects on the volcanism and seismotectonics of the interior of the Eurasian continent and mantle dynamics under this wide region.

Our present results on the origin of the active intraplate volcanoes in NE Asia suggest that not all the intraplate volcanoes are caused by deep mantle plumes (Wilson, 1963; Morgan, 1971). Some of the intraplate volcanism as that in NE Asia can be explained by the plate tectonic processes in the upper mantle and the mantle transition zone, as pointed out earlier by Anderson (1995) and Foulger (2003). However, the nature is complex, and various processes may coexist in the mantle. Some of the strong hotspots, such as those in Hawaii, Iceland, South Pacific and Africa, are associated with deep mantle plumes (Zhao, 2004, 2007).

5. Conclusions

We used a large number of arrival-time data from local, regional and teleseismic events to determine a 3-D P-wave structure of the crust and upper mantle under the Changbai volcanic area in Northeast Asia. Our results show a prominent low-velocity anomaly from the surface down to 410 km depth beneath the Changbai volcano and a broad high-velocity anomaly in the mantle transition zone, which are generally consistent with the previous global and regional tomographic studies for East Asia. Focal-mechanism solutions of deep earthquakes indicate that the subducting Pacific slab under the Japan Sea and the East Asia margin is subject to compressive stress regime. These results suggest that the Pacific slab meets
strong resistance at the 660-km discontinuity and so it becomes stagnant in the mantle transition zone under NE Asia. The upper mantle under NE Asia has formed a big mantle wedge (BMW) above the stagnant slab. The BMW exhibits low seismic-velocity and high electrical-conductivity, which is hot and perhaps also wet because of the deep dehydration reactions of the stagnant slab and the convective circulation process in the BMW. These processes lead to the upwelling of hot and wet asthenospheric materials and thinning and fracturing of the continental lithosphere as well as the formation of the active intraplate volcanoes in NE Asia. Therefore the active intraplate volcanism in NE Asia is not related to deep mantle plumes but is caused by the plate tectonic processes in the upper mantle and the mantle transition zone. A better understanding of these processes can be achieved by deploying a network of seismic stations on the Korea Peninsula and Japan Sea to determine higher-resolution mantle tomography under NE Asia in addition to conducting other geophysical and geochemical investigations of the region.

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