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Origin of the Changbai intraplate volcanism in Northeast China: Evidence from seismic tomography

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Abstract **Seismic images of the mantle beneath the active Changbai intraplate volcano in Northeast China determined by teleseismic travel time tomography are presented. The data are measured at a new seismic network consisting of 19 portable stations and 3 permanent stations. The results show a columnar low-velocity (–3%) anomaly extending to 400 km depth under the Changbai volcano. High velocity anomalies are visible in the mantle transition zone, and deep earthquakes occur at depths of 500—600 km under the region, suggesting that the subducting Pacific slab is stagnant in the transition zone, as imaged clearly also by global tomography. These results suggest that the Changbai intraplate volcano is not a hotspot like Hawaii but a kind of back-arc volcano related to the upwelling of hot asthenospheric materials associated with the deep subduction and stagnancy of the Pacific slab under northeast Asia.**

Keywords: Changbai volcano, intraplate volcanism, teleseismic tomography, subducting slab.

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In the Chinese continent there are many Cenozoic volcanoes, but only a few are still active now, such as Changbai and Wudalianchi volcanoes in Northeast (NE) China and Tengchong volcano in southwest China[1,2]. The Changbai intraplate volcano is located close to the boundary between China and Korea. It is also called Tianchi or Baitoushan 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[3]; seismic explosion studies found low-velocity anomalies in the crust and uppermost mantle under the volcano, which are considered to be associated with magma chambers[4]. Albeit these investigations, the origin of the Changbai intraplate volcano is still unclear. Some researchers consider it as a hotspot like Hawaii[5], while others consider that its formation is associated with the processes of deep subduction of the Pacific plate, upwelling of hot asthenospheric materials, and lithospheric rifting[1,6].

In order to clarify the origin of the Changbai volcano and its relationship to the deep structure and geodynamic evolution of the East Asian region, we have attempted to use teleseismic arrival time data recorded by a new temporary seismic network in NE China to determine a detailed three-dimensional (3-D) seismic velocity structure of the crust and mantle under the Changbai region. We also combine global tomographic images with the regional tomographic results to explore the origin of the intraplate volcanism in NE Asia.

1 Data and method

Because of the lack of digital seismic stations in NE China, the seismic structure of the crust and mantle under this region has not been determined well. In the summer of 1998, a portable seismic network of 19 stations was installed in the Changbai region[7]. Figure 1(a) shows the distribution of the 19 portable stations and three stations (MDJ, BJT, and HIA) which belong to the Chinese Digital Seismic Network (CDSN). We can see that these 22 stations have a dense and uniform distribution in and around the Changbai volcano. The three CDSN stations have recorded earthquakes since 1986. The 19 portable stations had been in operation since June 1998, some of them had continued till April 1999. We picked up 548 high-quality P-wave arrival times from 68 teleseismic events. Some of the waveforms are relatively noisy, so we used filters to reprocess the waveforms for removing the noises. Through these efforts we have attempted to collect the data as many as possible. The measured arrival time data have picking accuracy of 0.10—0.15 s.

Figure 1(b) shows the epicentral distribution of the 68 teleseismic events used in this study. These events are all greater than M 4.8. The hypocentral parameters are those redetermined by E.R. Engdahl (see ref. [8] for details). All of the teleseismic events were located in a range of 30°—90° from the seismic network except for an earthquake occurring in Kamchatka that is approximately 25° from the network. Thus, when relative travel time residuals from the teleseismic events are used for the tomographic inversion, the effects of structural heterogeneities in the hypocentral areas and those in the lowermost mantle can be greatly reduced (see ref. [9] for details).

Theoretical travel times were calculated by using the iasp91 one-dimensional Earth model[10], and were corrected for the Earth's ellipticity[11]. When calculating the theoretical travel time, we also determine the ray path from the hypocenter to the station, and locate the intersection between the ray path and the edge of the model space. Then the ray path from the intersection to the station is determined by using a 3-D ray tracing technique[12]. This 3-D ray tracer is very accurate and efficient, and can deal with a 3-D velocity model containing several complex velocity discontinuities (such as the Moho and 660-km discontinuities) (see refs. [9,12] for details).

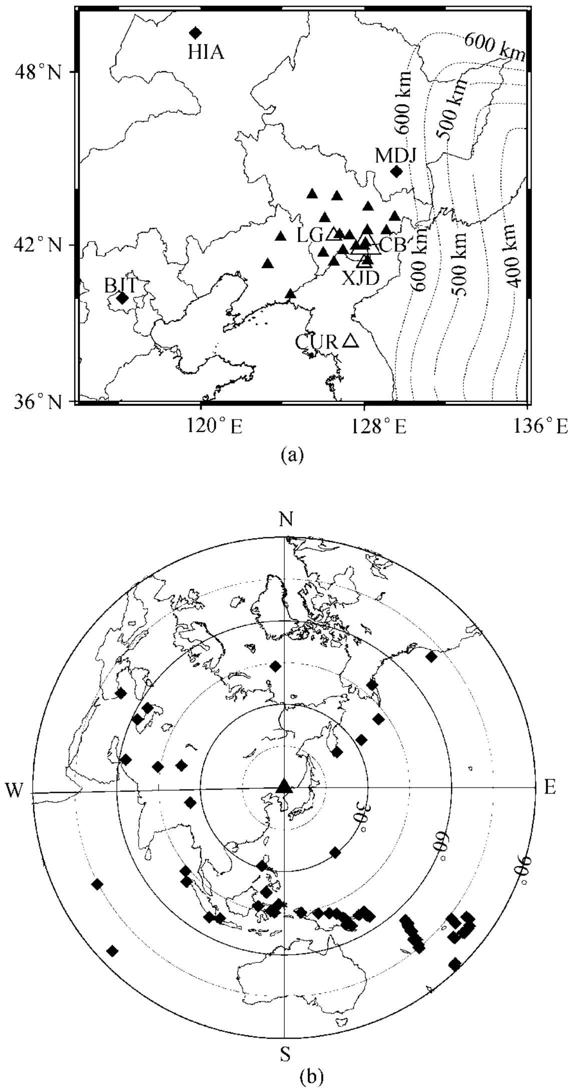


Fig. 1. (a) Map showing the locations of 19 portable seismic stations (solid triangles) and three CDSN stations (diamonds). The dotted lines show the depth contours of the Wadati-Benioff deep seismic zone in the subducting Pacific slab. Open triangles show the active intraplate volcanoes in northeast Asia. CB, Changbai; LG, Longgang; XJD, Xianjindao; CUR, Ch'Uga-Ryong. (b) Epicentral locations of the 68 teleseismic events used in this study. The solid triangle shows the location of the Changbai volcano. The numbers denote the distance (in (°)) to the Changbai volcano (1° = 111.19 km).

A 3-D grid net is set up in the modeling space to express Earth structure. Velocity perturbations at the grid nodes from the iasp91 1-D velocity model[10] are taken as unknown parameters. The velocity perturbation at any point in the model is computed by linearly interpolating the velocity perturbations at the eight grid nodes surrounding that point. A damped least-squares method is used to invert the relative travel time residuals, resulting in a 3-D P-wave velocity model of the study area.

2 Analysis and results

Synthetic tests are an effective way to evaluate the reliability and resolution of an inverted tomographic result[9,13]. In this paper we conducted a number of synthetic tests with input velocity models that have different grid spacings. The test results show that with the available rays in our data set (Fig. 2) the optimal grid spacing is 2°×2° in the horizontal directions and 90—200 km in depth. Due to the limited space, only two examples of the synthetic tests are shown here (Fig. 3). In the first test, the input velocity model contains a low-velocity (low-V) column from the surface to 800 km depth under the Changbai volcano (Fig. 3 (a) and (c)). The low-V column has a velocity 3% lower than the iasp91 model. In the second test, the input model contains a low-V column (–3%) at depths of 0—400 km and a high-velocity (high-V) column (+3%) at depths of 400—800 km under the Changbai volcano (Fig. 3 (e) and (g)). Then a synthetic data set of relative travel-time re-

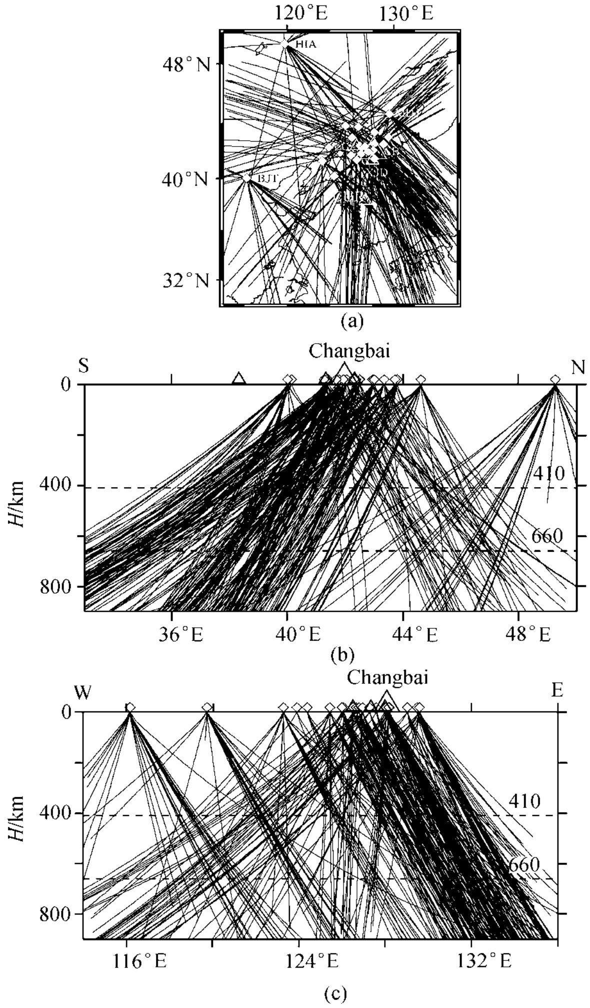


Fig. 2. Distribution of seismic rays used in this study in plane view (a) and in (b) north-south and (c) east-west vertical cross sections. Diamond symbols denote seismic stations. Open triangles show the intraplate volcanoes.

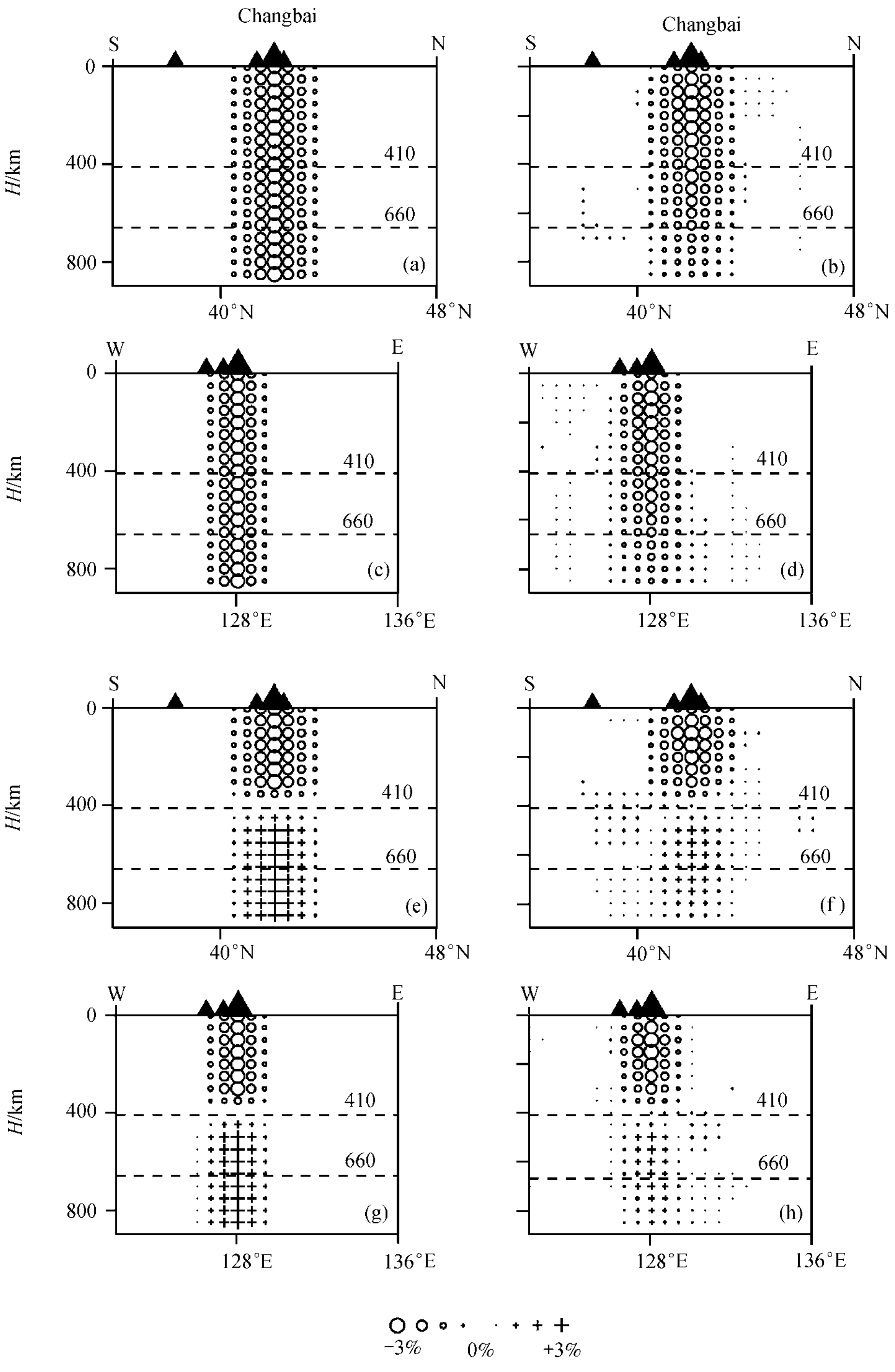


Fig. 3. Input models (left) and inverted results (right) of the synthetic tests along the north-south ((a), (b), (e), (f)) and east-west ((c), (d), (g), (h)) vertical cross sections (see text for details). Circles and crosses denote slow and fast velocities, respectively. Solid triangles show the volcanoes. The two dash lines denote the 410 and 660 km discontinuities.

siduals are calculated for each of the input models. The numbers and locations of earthquakes, stations and ray paths in the synthetic data set are the same as those in the observed data set. Then we invert the synthetic data to obtain the output models (Fig. 3 (b), (d), (f) and (h)) which are the reconstructed images of the input models.

Figure 3 shows that the patterns of the input models are well reconstructed, though there are some differences in the amplitude of the velocity anomalies. These tests suggest that our tomographic results are reliable down to about 800 km depth under the Changbai volcano. This is also clear from the distribution of the rays in our data set (Fig. 2) which shows that rays have a good coverage and crisscross well down to 800 km depth under the Changbai volcano.

Figure 4 shows the tomographic images under the Changbai volcano obtained by using the observed data (Figs. 1 and 2). A prominent low-V zone (–3%) exists down to about 400 km depth under the Changbai volcano and has a lateral extent of about 200 km. It has a dipping geometry under the volcano, which may be related to the distribution of several small volcanoes[14] around the

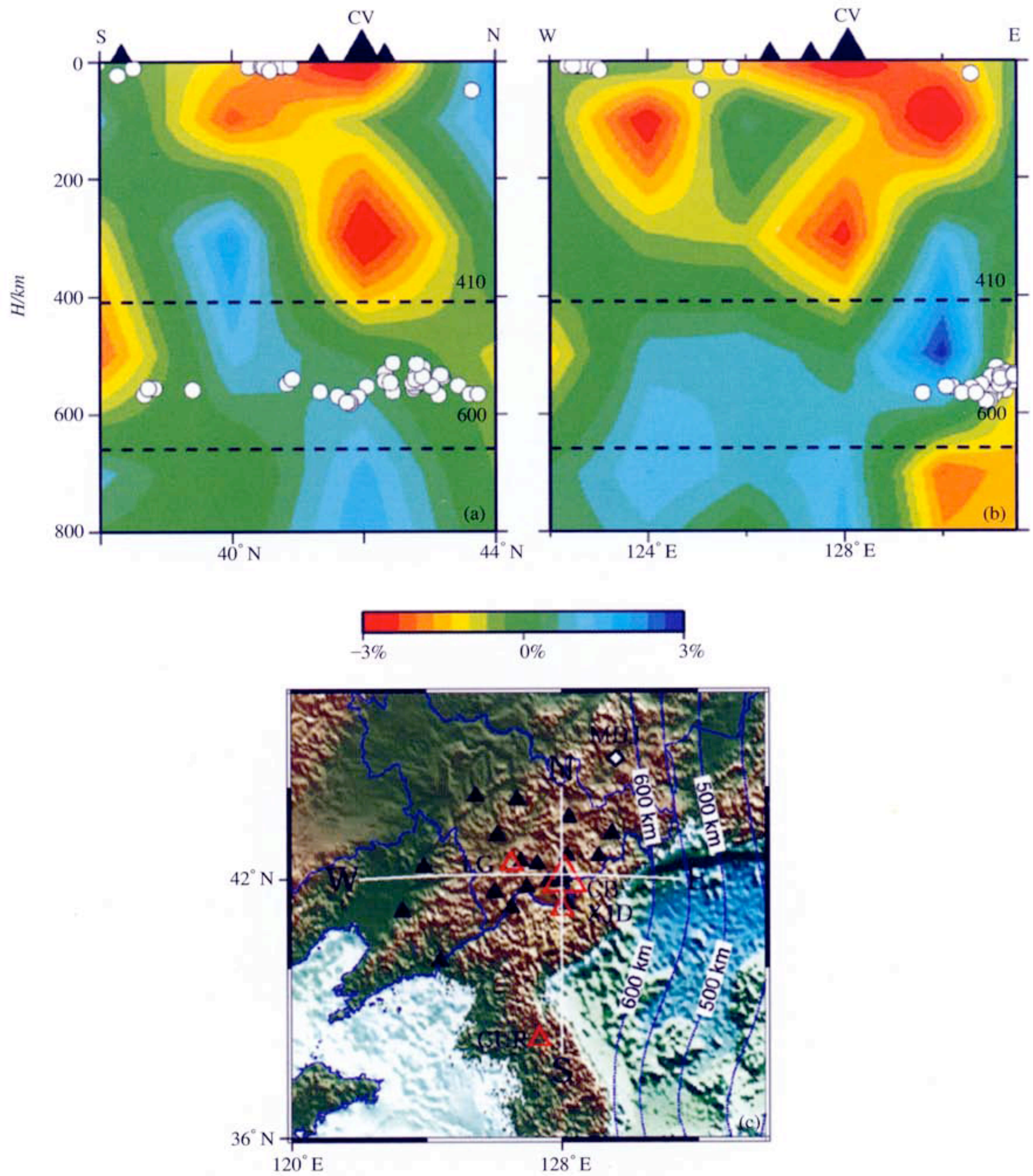


Fig. 4. North-south (a) and east-west (b) vertical cross sections of P-wave velocity images obtained in this study. Red and blue colors denote slow and fast velocity anomalies, respectively. The velocity perturbation scale is shown below the cross sections. Black triangles denote the volcanoes. White dots show the earthquakes that occurred within a 200-km width of the profile. (c) Map showing locations of the two cross sections in (a) and (b). Red and black triangles denote intraplate volcanoes and 19 portable seismic stations, respectively. The white diamond denotes the CDSN station (MDJ). The dotted lines show the depth contours of the Wadati-Benioff deep seismic zone in the subducting Pacific slab.

Changbai volcano and complex ascending paths of hot magma chambers. High-V anomalies are visible in the mantle transition zone under the Changbai volcano (Fig. 4), and many deep-focus earthquakes occurred in the high-V zones. Hence we believe that the high-V anomalies represent the subducting Pacific slab that is stagnant in the mantle transition zone under NE China.

3 Discussion

Figure 5 shows two vertical cross sections of velocity images under the Changbai and Wudalianchi volcanoes from a global tomography model[15]. In addition to the first P wave data, later phase data of pP, PP, PcP and Pdiff waves were also used in the inversion, and depth variations of the Moho, 410 and 660 km discontinuities were also taken into account. For the effects of the discontinuity topography on the ray paths and travel times, see ref. [16] for details. In the upper mantle, the subducting Pacific slab is imaged clearly and earthquakes occurred down to about 600 km depth within the slab (Fig. 5). Under NE China, the slab becomes stagnant in the transition zone. In the lower mantle, pieces of fast anomalies are visible under the stagnant slab in the transition zone. Similar features were also found in other global tomographic models[17−19]. These results suggest that the subducting slab 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 finally collapses to fall down to the core-mantle boundary because of very large gravitational instability from phase transitions. A few researchers used receiver function

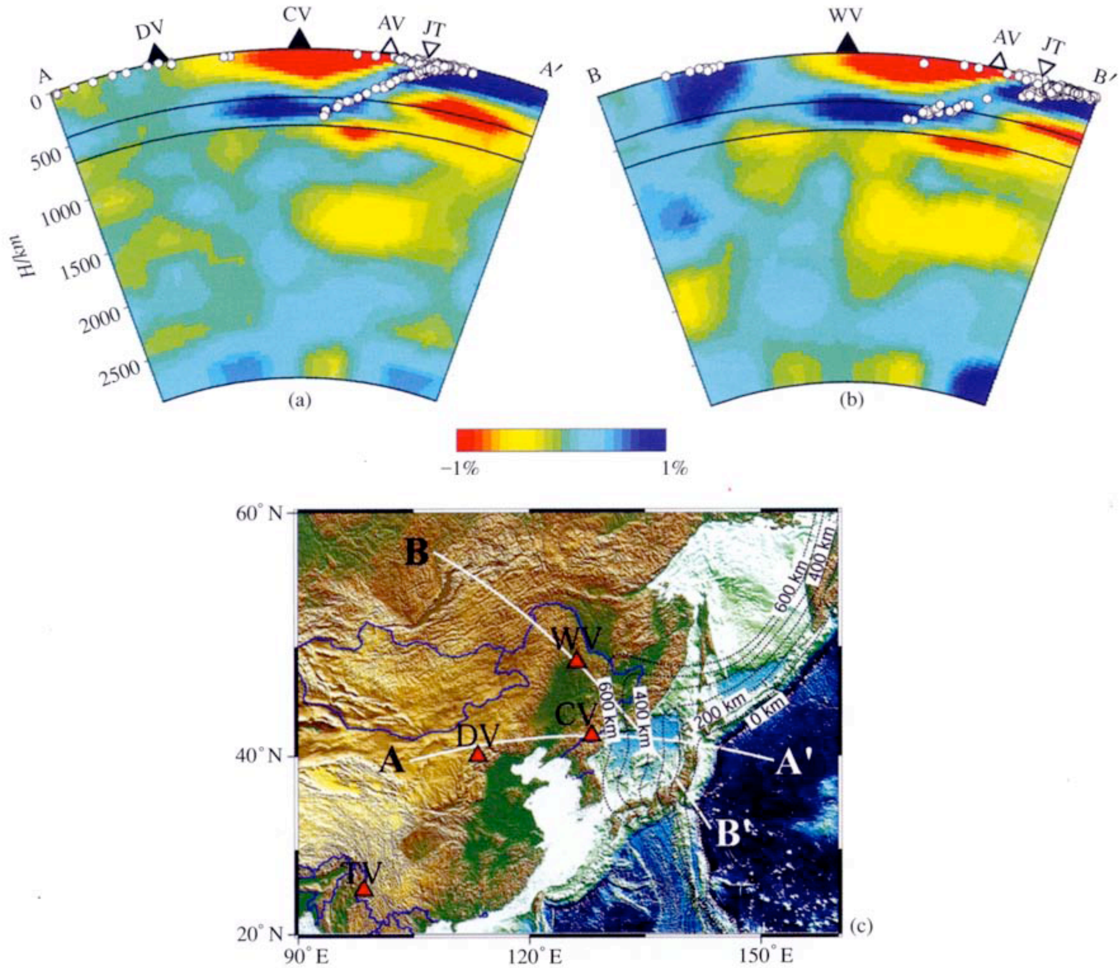
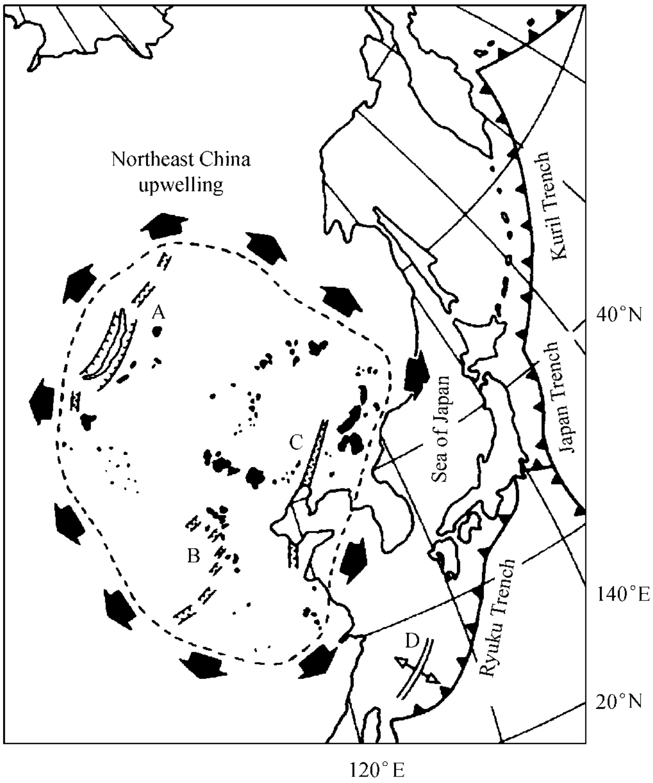
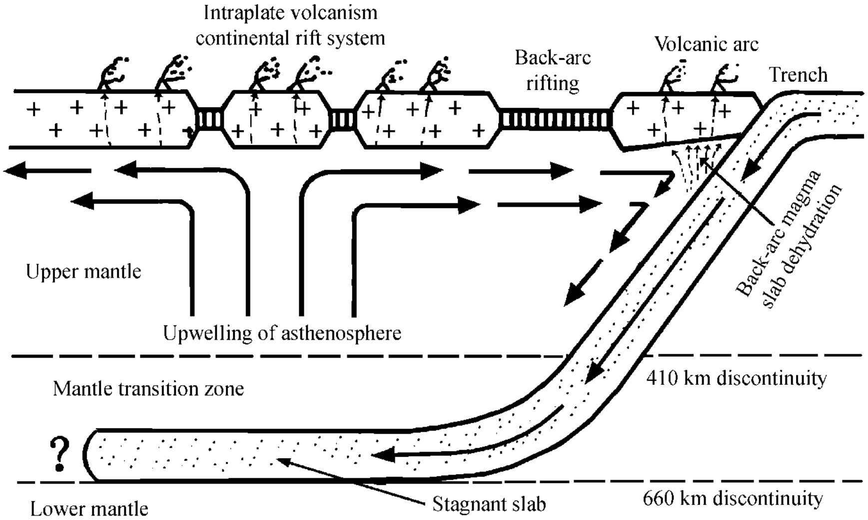


Fig. 5. (a) and (b) Vertical cross sections of P-wave velocity images determined by a global tomographic inversion[15]. Red and blue colors denote slow and fast velocities, respectively. The velocity perturbation scale is shown below the cross sections. White dots denote earthquakes within 150 km of the profiles. Open triangles show the arc volcanoes (AV). The reversed open triangles show the locations of the Japan Trench (JT). Solid triangles denote intraplate volcanoes: CV, Changbai; WV, Wudalianchi; DV, Datong; TV, Tengchong. (c) Map showing locations of the two cross sections in (a) and (b). Red triangles denote intraplate volcanoes. The dotted lines show the depth contours of the Wadati-Benioff deep seismic zone in the subducting Pacific slab.



(a)



(b)

Fig. 6. (a) Tectonic features on the surface 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 mantle wedge and deep dehydration process of the subducting slab cause upwellings of hot asthenospheric materials, leading to the formation of the continental rift systems as well as intraplate volcanoes in northeast Asia (modified from ref. [6]).

methods to analyze the waveform data from the portable seismic network (Fig. 1) and obtained the similar results[20,21]. Fig. 5 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. This result is 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[22].

There are several types of volcanoes on Earth: mid-ocean ridge volcanoes, subduction zone volcanoes, hotspots caused by mantle plumes, and intraplate volcanoes associated with upwelling of hot asthenospheric materials and lithospheric fractures[6,14,23]. Apparently, the Changbai volcano is not a mid-ocean ridge volcano. Because the subducting Pacific slab is stagnant in the mantle transition zone under NE China, the Changbai volcano is not a hotspot like Hawaii, Iceland, and Eifel in central Europe[15,24,25].

Recent studies[26] show that not all the plate boundaries are narrow deformation zones as assumed by the theory of plate tectonics when it was first proposed. Some plate boundaries can be very broad deformation zones, for example, the continental collision between the Indian and Eurasian plates has resulted in the Tibet Plateau of several thousand kilometers wide. The Changbai volcano is located in the interior of the Eurasian continent, leaving the Japan Trench farther than 1000 km. In addition, the stagnant Pacific slab exists in the mantle transition zone under NE China. Hence the origin of the Changbai volcano is also different from that of the arc volcanoes on the Japan and Kuril islands.

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[9,22]. These processes may have led to the large-scale upwelling of hot asthenospheric materials under NE China and caused the intraplate volcanism and continental rift systems in the region. Because the very old (hence very cold) Pacific plate is subducting beneath eastern Asia at a rapid rate (7—10 cm/a), 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. This scenario has been demonstrated by experimental petrology and other studies[27, 28]. Deep dehydration reactions of the rapidly subducting Pacific slab have also been found in the Tonga subduction zone[22].

Based on these results, we believe that the Changbai volcano is a kind of back-arc intraplate volcano whose formation is closely related to the deep subduction and stagnancy of the Pacific slab in the transition zone as well as its deep dehydration processes. Tatsumi et al.[6] 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 role of the stagnant Pacific slab in the formation of the intraplate volcanism in East Asia (Fig. 6 (b)). The extensional rift systems and faults widely existing in East Asia (Fig. 6 (a)) may be the surface manifestation of a deep dynamic process such as deep subduction of the Pacific slab, upwelling of hot asthenospheric materials, and lithospheric fractures.

4 Conclusions

We applied a teleseismic tomography method to a large number of high-quality arrival times recorded by a newly installed portable seismic network to investigate the structure and origin of the Changbai volcano in Northeast China. Our results indicate that the Changbai volcano is not a hotspot like Hawaii but a kind of back-arc intraplate volcano closely related to the deep subduction and dehydration of the Pacific slab as well as its stagnancy in the mantle transition zone under northeast Asia. We can say that the Changbai volcano is a close relative of the arc volcanoes on the Kuril and Japan islands.

Global tomographic images show that the large-scale structure under the Wudalianchi volcano is quite similar to that under the Changbai volcano (Fig. 5). Hence it is possible 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 to determine a detailed 3-D structure of the crust and mantle, in a way similar to the present study. Such an effort will be very important for clarifying the geological evolution and deep dynamic processes of the northeast Asian region.

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