Seismic tomography of the northwest Pacific and its geodynamic implications*

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Received February 16, 2000; revised March 27, 2000

Abstract High-resolution tomographic images across Japan Trench-Changbai Mountains-Dong Ujimqinqi are displayed, showing the morphological feature of the subducted slab in the northwestern Pacific margin and the characteristics of lithosphere structures under the Changbai Mountains and the Da Hinggan Mountains. The Pacific plate began to penetrate into the deeper mantle after it subducted to the 660 km discontinuity with an underthrusting angle of 26°, but did not continue to move further westward. In contrast, there appeared a remarkable thermal upwelling zone to the west of the downward plate. In addition, the evidence from the subduction time and time lag between the subduction and consequent magmatism indicates that there is no direct genetic correlation between the Mesozoic magmatism in eastern China and subduction of the Pacific plate. In this work, we also emphasize that what the tomographic images reflect is the present structure in the deep earth interior, which should preserve some Mesozoic lithospheric structure characteristics. In summary, we attribute the Mesozoic intense magmatic evolution in north China to the intraplate asthenosphere upwelling zone.

Keywords: seismic tomography, Pacific plate, subduction, continental margin volcano-plutonic rock belt.

Since the plate tectonics began to be well accepted in China in 1980s, many geologists have related the widely distributed Mesozoic intermediate-acid intrusive and volcanic rocks in eastern China to the westward subduction of the Pacific plate[1,2]. For instance, Cheng interpreted the Mesozoic volcanism in the Da Hinggan Mts. as the result of the long-distance effect of underthrusting of the Pacific plate[3]. Zhao et al. even suggested that the Mesozoic volcanic activities in Xianghuang Qi, around 2400 km away from the present subduction zone, were triggered by underthrusting of the Pacific plate under the Asia continent with a relatively low underthrusting angle of 4°[4]. As a matter of fact, however, the precise configuration of the subducted Pacific plate, the range affected by the subduction, and the relationship between the subduction and the Mesozoic magmatism in the Asia continental margin remain unknown. In this paper, we present a new seismic tomography of the northwestern Pacific to show the configuration of the subducted Pacific slab and on the basis of it, we will attempt to make a preliminary discussion on the range affected by the subduction. Further study on the relationship between the Mesozoic magmatism in the eastern Asia continental margin and the subduction based on a large amount of petreology and geochemistry of the Mesozoic volcano-plutons will be presented in another paper.

* Project supported by the National Natural Science Foundation of China (Grant Nos. 49672156 and 49872079), and National High Technology Research and Development Plan (863-820-01-04).

1 Seismic tomography of the northwestern Pacific subduction zone

Recently, we determined the three-dimensional structure of tomographic P wave velocity of the region ranging from 115°E to 155°E and from 15°N to 55°N (Plate I A), by deploying 155795 and 42559 P arrivals from 10603 earthquakes in the study area and 2309 earthquakes in the adjacent areas, respectively. In the data set, 373 deep earthquakes largely improved the reliability and resolution of the inversion for the upper mantle and subducted slabs as shown in Plate I B(a). Plate I B(a) is a cross section from Japan Sea, through the Changbai Mts. to Siping City. The configuration of the subducted Pacific slab is clearly shown on this image. The slab is deformed obviously at depth of 300 km—400 km, where olivine is believed to converse to modified spinel, and near the boundary between the upper and the lower mantle, i.e. at 660 km discontinuity, the slab appears to be stagnant, and then the slab sinks into the lower mantle steeply. In contrast, to the west of the downward plate there appears a remarkable thermal upwelling zone in which a low velocity section goes upward to 40 km—60 km. If we project the earthquakes in the strip along the section with a width of 50 km on the subducted slab, it can be found that earthquake hypocenters are concentrated to an area just above the 660 km discontinuity from where the subducted slab penetrates into the lower mantle. This area is right in Hunchun, a famous deep focus earthquake zone in China. The low velocity upwelling from 130°E to 132°E is interpreted as the back arc opening of Japan Sea, whereas the low velocity zone east of 125°E at depth from 40 km to 60 km is clearly correlated to the volcanism of the Changbai Mts., where volcanic activities have been intensive since the Miocene, especially, the Pleistocene.

2 Spatio-temporal range affected by the subduction

Zhang and Tang[5] proposed a plate-underthrusting model to calculate the temperature distribution within the subducted slab at various depths, taking the thermal conduction between the mantle material and the lithospheric plate into consideration. The calculation shows that when the subducted slab reaches the depths more than 600 km, the temperature at its center will be higher than 1200℃, and such a temperature is high enough to lead to the intenerating even partial melting of rocks in the slab and earthquake will consequently occur without elastic faulting. The subducting angle and depth make it possible to calculate the horizontal distance from the beginning of the subduction to the position where the slab breaks off and the result is not more than 1230 km. However, the distance from the arc volcano-pluton or the MORB (mid-oceanic range basalt) correlated to back arc opening to the subduction zone is commonly less than 1000 km, suggesting that arc-related magma are impossible to penetrate into the low velocity upwelling east of 125°E and move westward by detachment of the intracontinental lithosphere. Even though the position of the Japan arc formed before the opening of Japan Sea[6] is concerned, the location where the subducted slab finally breaks off will not be beyond Changchun and Shenyang cities. Therefore, it is difficult to attribute the Mesozoic magmatism of the Da Hinggan Mts.-Yanshan Mts.-Taihang Mts. to the subduction of the Pacific plate.

In term of thermal conduction, there is certainly a time lag between subduction and arc magmatism. In their research on the thermal processes beneath Japan island arc and the origin of marginal sea, Ueda and Sugimura suggested that the cooling effect of distinct decrease of isotherm due to the underthrusting of the lithospheric plate will lead to a heat flow of 1HFU ($= 1 \times 10^{-6} cal/cm^2 \cdot s$) produced above the subducted slab, which needs at least several times heat under the slab[7]. According to a model proposed by Hasebe in which he assumed a lithosphere slab with a thickness of 100km underthrusts at a rate of 3 cm/a along a dipping angle of $tg\theta = 1/3$ (i.e. 18.43°), it would take 100 Ma to generate the heat and effective thermal conduction rate which is necessary for present heat flow distribution observed in Japan Sea and adjacent area[7]. It can thus be inferred that the subduction providing the high heat flow and leading to the opening of Japan Sea and the corresponding volcanism might take place 100 Ma ago. This result is in good agreement with the well-accepted subduction history of the Pacific plate. The isotopic ages of Sanbakawa-Liaoka bi-metamorphic belt in Japan are concentrated to the period of 105Ma—110Ma[8], suggesting that the subduction took place approximately in the late period of the Early Cretaceous when Japan island was still on the Asia continental margin. It is no doubt that the bi-metamorphic belt is the product of the underthrusting of the oceanic plate under the Asia continent. The age distribution of the Pacific oceanic floor[9] shows that the large scale spreading of the Pacific plate began at the Late Cretaceous (84 Ma). In Japan, the Palaeogene volcanic rocks are seldom observed and it was not until the Neogene when the volcanic rocks occurred abruptly[9], indicating that Japan island arc was formed in the Neogene. Moreover, the back arc basin-Japan sea did not open until 28 Ma—15 Ma[10]. In addition, there seems no Andean type arc magmatism associated with the subduction of the Pacific plate in the Late Mesozoic as far as the thermal evolution of the lithosphere is concerned. Thus we can believe that volcano-plutons from the Late Jurassic to the Early Cretaceous is also not correlated genetically with the subduction of the Pacific. If the aforementioned thermal conduction model is right, and if we assume that the Late Jurassic——the Early Cretaceous volcano-plutons are associated with subduction of the oceanic plate, then the subduction should have taken place during 245 Ma—210 Ma. In the Early Mesozoic, however, the Asia continent was in the process of collage and no evidence for a subduction of the palaeo-oceanic plate has been found.

4 Relationship between Mesozoic magmatism and deep tectonics in northern China

Someone may ask whether it is appropriate to use seismic tomography data to interpret the Mesozoic tectonic setting. We think that what can be derived from the present geophysics data is the tectonic information now existing in the deep earth, it does not mean that the tectonic forms at present or has been existing from the Cenozoic on. By tomography, Grand deduced that beneath the North America continent, there still exists the residue of subducted Falaron plate, which are considered to have disappeared from the surface of the earth in the Mesozoic[11]. Most recently, Van der Voo et al. advanced the geological interpretation of seismic tomography by recognizing the likely connection between a major high-velocity anomaly lying from 1500 km to 2800 km beneath Siberia and the subduction of an oceanic plate during Jurassic (150Ma—200Ma)[12]. Richards reviewed this result and further confirmed that seismic tomography is a powerful tool for palaeogeography and can provide a fresh source of information about the history of the global plate motion and the processes of continental growth[13].

As illustrated in plate I B(b), an apparent low velocity section, overlaid by a 100 km high velocity zone, penetrates downward directly to the 670 km discontinuity beneath the Da Hinggan Mts. (119°E—121°E). It suggests that magmatism in the Da Hinggan Mts. is correlated with the upwelling of the upper mantle materials. The tomographic image of the north China craton shows that many irregular materials perhaps come from the asthenophere upwell and interlude into the dismembered ancient basement of the Craton[14, 15]. Besides, several high velocity residues have been observed in the depth of approximately 100 km (about the top of asthenosphere) beneath the Zhangjiakou-Xuanhua area, Harqin area, Hehuai area, and Bohai Bay[16], reflecting an intense mantle-crustal interaction in these areas. These indicate that the Mesozoic magmatism in the Da Hinggan Mts., even the north China, is genetically correlated with the upwelling of the sub-continental mantle material, but not with the subduction of the Pacific plate. A detailed research on the petrology and geochemistry of the Mesozoic volcano-plutons also supports this suggestion[17].

The seismic tomography of the East Asia continental margin indicates that this technique can help us trace the evolutionary history of tectonics. Provided that the subducted slab broken-off about 150 Ma—200 Ma ago can be preserved, as illustrated by Van der Voo et al.[12], the Mesozoic tectonics associated genetically with magmatism can also inevitably be imprinted on the seismic tomographic image. A multidisciplinary synthetical research can reveal more information.

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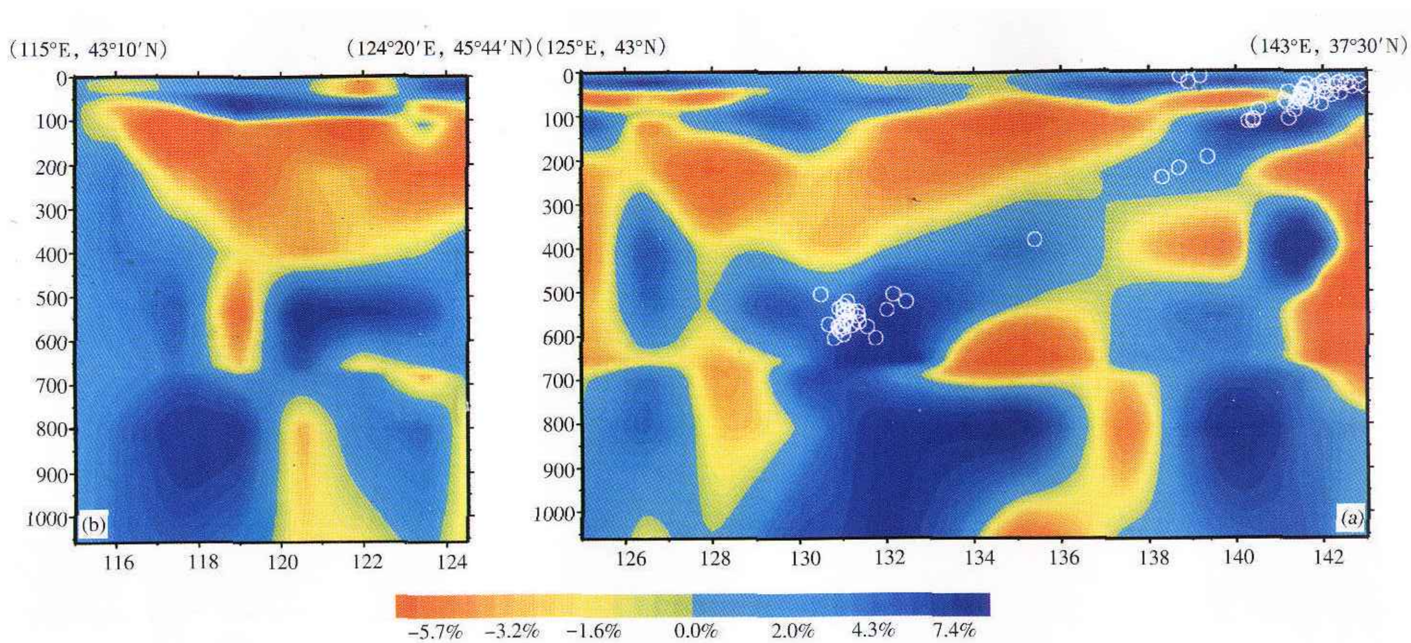

Seismic tomographic image crossing the Pacific Ocean subducted slab (a) and crossing the Da Hinggan Mountains (b)
Red in the colorful scale denotes the region with negative disturbance and higher temperature while blue denotes the region with positive disturbance and lower temperature