Pn WAVE VELOCITY AND ANISOTROPY IN THE NORTHEASTERN SOUTH CHINA SEA AND ADJACENT REGION

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Abstract Using seismic data from Chinese and ISC stations between 1980∼2004, we inverted Pn wave velocity structure and anisotropy of the northeastern South China Sea and adjacent region. The velocity variations at uppermost mantle reflect the features of regional geology and tectonics. Southeastern China has fast velocities, correspondent to the lithospheric mantle in tectonically stable regions. Slow velocities appear near the Binhai fault zone along the coast of southeastern China, which indicates a possible penetration of the fault zone into the uppermost mantle. Similar to southeastern China, fast velocities throughout the northern South China Sea and Taiwan Strait reveal a property of the lithospheric mantle in continental margin, while fast velocities in the Xisha Trough reflect a southward extension of continental shelf and a mantle upwarm produced by Cenozoic rifting. There is no evidence of large-scale mantle heat flows in the northern South China Sea. However, a very slow velocity anomaly is observed in the eastern sub-basin of the South China Sea, where is an extinct mantle upwelling center with high heat flows, indicating a thinning or removal of lithospheric mantle. Along the eastern Taiwan, Luzon and northern Philippine, slow velocities are closely related to seismic and volcanic activity and magmatism in the arc zone, while fast velocities in the eastern South China Sea and western Philippine Sea reflect the character of oceanic lithospheric mantle. Pn velocity anisotropy also reveals the stress state in regional tectonics and the history of deformation of lithospheric mantle. Southeastern China has small anisotropy in response to less deformation there. Anisotropy is observed in the northern South China Sea, with fast directions of anisotropy aligned with shallow structures in crust, which reflect the evidence of the Mesozoic-Cenozoic rifting and shear deformation in lithospheric mantle. Strong anisotropy is also found along the Ryukyu-Taiwan-Luzon arc zone, with fast directions parallel to trenches, which indicates that strong deformation of lithospheric mantle in the leading edge of the Philippine Sea plate and Eurasian continent. The change of the fast directions of anisotropy near the eastern Taiwan is probably caused by a conversion of collision mechanisms between the Eurasian continent and the Philippine Sea plate, and the tear of the lithosphere.

Key words Northeastern South China Sea, Pn wave velocity, Anisotropy, Lithosphere mantle

1 INTRODUCTION

Located in a conjunctive region between the Eurasian continent and the western Philippine Sea plate, the northeastern South China Sea is an important site for the study of the continental margin rifting and plate collision mechanism. Extending from southeastern China, the continental shelf of the northern South China Sea experienced the Mesozoic-Cenozoic rifting and resulted in several pull-apart basins from southeast of the Hainan Island to southwest of the Taiwan Island. Crustal thickness decreases from the northern continental shelf to the central basin of the South China Sea, accordingly, the lithosphere has been thinned and mantle underplating is suspected to exist in the lower crust[1∼7]. Even so, the origin of the rifting and the tectonic type (volcanic or non-volcanic) of the continental margin are still debated. A major reason is the lack of sufficient geophysical data. In the eastern South China Sea, the Philippine Sea plate moves to northwest at a rate of 7∼9 cm/a, while the South China Sea plate moves at a slow rate of 1 cm/a in the same direction[8]. Because the motion of the Philippine Sea plate is much faster than that of the South China Sea plate, a strong convergence between two plates produces two opposite subduction systems along the Philippine Trench, eastern Luzon Trough and Manila Trench. The plate motion caused the Luzon block to be dragged westward and pushed over the South China Sea plate. Therefore, the eastward subduction of the South China Sea plate is practically explained by a westward overthrust of the Luzon block. This arc zone is also characterized by strong seismic, volcanic activity

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and intense magmatism. To address above questions, we need to further study the structure and tectonics, deformation pattern and dynamic character of the lithosphere of the northeastern South China Sea. Although Chinese researchers studied the velocity structures of the lithosphere of the Chinese marginal seas by using P and S wave tomography\(^{[9\sim13]}\), their resolutions are insufficient for the study of the deep tectonics in the northeastern South China Sea. Other researchers studied the uppermost mantle structure of the Chinese continent by Pn tomography\(^{[14\sim16]}\), but their results cannot cover the northeastern South China Sea, because of a lack of data in this region. For these reasons, in this paper, based on the method proposed by Hearn\(^{[17]}\) and using Pn data from the Chinese earthquake bulletins and the International Seismological Center (ISC) bulletins, we inverted the Pn velocity and anisotropy of the northeastern South China Sea and adjacent region. Our objective is to seek new information for analysis of uppermost mantle structure and tectonics.

2 DATA AND METHOD

2.1 Data

The data used in this study are Pn wave arrival times from the Chinese earthquake bulletins and the International Seismological Center bulletins between 1980~2004. Pn data recorded by the stations in Chinese continent and Taiwan region provide the ray coverage over the southeastern China and adjacent seas, while Pn data from the ISC stations largely complement the ray coverage of the Luzon and northern Philippine. Taken together, these data are effective to increase the resolution level of the inversion for the northeastern South China Sea. A lot of stations and abundant earthquakes along the Ryukyu-Taiwan-Luzon arc zone provide sufficient Pn data for our study, even after applying strict selection criteria to them.

To distinguish Pn arrivals from the dataset, we first analyzed the change of Pn travel times with epicentral distances. An average Pn velocity of 7.9 km/s was obtained from the slopes of fitted curves and this value is equivalent to average Pn velocity in eastern China\(^{[14\sim16]}\).

Several criteria were used for Pn data selection. The epicenter distance is required to be between 160~1500 km; the depths of earthquakes are limited less than 32 km; each station is required to have recorded at least
ten earthquakes and each earthquake has to be at least recorded by four stations. Reduced travel times are limited to lie between 2∼11 seconds in order to prevent misidentification of Pg and Pn phases (Fig. 2). After applying the criteria to the data, we obtain 79034 Pn arrivals from 7292 earthquakes. The data coverage indicates that the northeastern South China Sea is well sampled by dense Pn wave paths from different azimuths, particularly in the southeastern China and Ryukyu-Taiwan-Luzon arc zone (Fig. 3).

2.2 Method

We used Pn tomography method proposed by Hearn to invert Pn velocity and anisotropy[17]. The uppermost mantle of the study area is divided into a set of two-dimensional cells 0.5° × 0.5° in the longitude and latitude. Crustal model referred to a smooth global model CRUST 2.0[18]. A flat-layered earth model contains a Pn velocity of 7.9 km/s and a crustal thickness of 32 km. This is because the crustal thickness beneath most stations is approaching to this value. After several tests with different parameters, the Pn travel times calculated from this model are well fitted with observed ones.

We used a damped LSQR algorithm to solve the sparse linear system of equations[19]. Considering an unevenness of wave paths and data errors can make the linear equation system ill-conditioned, which may result in unreasonably high or low velocity anomalies, we added smoothness constraints to ensure the stability of the inversion. The smoothness constraints restricted our analysis to large-scale variations, while smaller scale anomalies were ignored. In order to outline major tectonic features and restrict unnecessary local anomalies, we made many tests with different damps and smoothness factors. After analysis and comparison, we choose a resolution damped by 200 and smoothed by 300 as our final result. The RMS error of travel time residuals was reduced from 1.90 before the inversion to 1.02 after the inversion.

2.3 Resolution

A checkerboard test was used to examine our model resolution based on existing Pn data. Fig. 4 shows a recovered Pn velocity and anisotropy images. For Pn velocity, the input is a sinusoidal pattern with amplitudes of ±0.3 km/s relative to a background velocity of 7.9 km/s. For anisotropy, the input is a sinusoidal pattern of 3% in amplitudes with alternating N-S and E-W fast directions. In the areas with dense ray coverage, such as the southeastern China, southern Ryukyu, Taiwan region, Luzon and northern Philippine, the patterns and amplitudes of Pn velocity anomalies are well recovered. In the northeastern South China Sea, the patterns of Pn velocity anomalies are recovered, but their amplitudes are reduced somewhat. Similar features are observed from the recovered anisotropy image. Above analysis indicates that the Pn tomography based on existing data can obtain resolutions in the northeastern South China Sea, and resolutions are particularly good in the Taiwan and Luzon regions with dense ray coverage, but become poor in the edges of the study region. They indicate that the level of the resolution is largely dependent on ray coverage and azimuths. These features are correlated with the ray paths of Pn waves in Fig. 3.
3 RESULT ANALYSIS

Figure 5 shows Pn velocities in the northeastern South China Sea and adjacent region. Relative to an initial velocity of 7.9 km/s in the reference model, Pn velocities vary between 7.6∼8.2 km/s. Their variations are related to regional tectonics, heat flows, particularly to temperatures of uppermost mantle. Studies of Pn velocity in the Chinese continent have shown that tectonically active regions with high heat flows often have slow Pn velocities, while tectonically stable regions generally have fast Pn velocities\cite{14∼16}.

3.1 Pn Velocity

Pn velocities in southeastern China are 8.0∼8.1 km/s and they decrease to 7.9 km/s in the southeastern coast, even less than 7.9 km/s in the Pearl River mouth, Zhangzhou and Shantou areas. These characters of Pn velocities are correlated with lithospheric thickness and heat flows in southeastern China\cite{20∼22}. Previous studies indicate that southeastern China has a relatively thick crust and lithosphere with fast average P and S wave velocities\cite{9∼13}, low heat flows (compared with those in the South China Sea)\cite{21,22}, weak historic and present seismic activity. Southeastern China is therefore considered as one of tectonically stable regions in Chinese continent. However, the thickness of lithosphere in the southeastern coast is decreased, while the heat flows are increased accordingly. Tectonically, the southeastern coast is correspondent to the Binhai fault zone where several strong earthquakes occurred near the Pearl River mouth, Shantou and Zhangzhou areas with slow Pn velocities. An onshore-offshore seismic sounding experiment indicates that the depth of the Binhai fault zone is approaching to the Moho, acting as a border between a continental crust of southeastern China and a thinned crust of the northern margin of the South China Sea. This character is also clear on gravity and magnetic anomalies\cite{23}. The slow Pn velocity shows again that the Binhai fault zone penetrates into the Moho and controls the heat flow activity in the uppermost mantle.

Bordered by the Binhai fault zone to the north, Pn velocities are 8.0∼8.1 km/s from the northern South
China Sea to the Taiwan Strait. These values are very similar to the uppermost mantle velocities beneath the ESP and OBS experiment profiles across the northern South China Sea\cite{2\textasciitilde7}. Actually, the northern margin of the South China Sea and the Taiwan Strait are seaward extensions of the southeast China continent. Their average heat flows are lower than those in the central basin of the South China Sea, approaching to those in southeastern China. The fast Pn velocity in these regions indicates that the northern South China Sea has a lithospheric mantle similar to southeastern China. We infer from above evidence that there is no large-scale mantle upwelling beneath those graben-type pull-apart basins such as the Qiongdongnan and Pearl River Mouth basins. That suggests a pull-apart mechanism within the crust, not extending into the uppermost mantle and showing the character of deep structures on the non-volcanic continental margins. As to the fast Pn velocities beneath the Xisha Trough, they not only reflect the southward extension of the southeastern Chinese continent, but also are related to the mantle upwarp in response to the pull-apart of the crust. The OBS experiment profile across the Xisha Trough shows a north-to-south symmetric thinning of the crust and the mantle upwarp, with P wave velocity of 8.0 km/s at the uppermost mantle, revealing the extension of the Cenozoic rift\cite{3,24}.

Pn velocities near the Manila Trench and in the eastern South China Sea are 8.0\textasciitilde8.2 km/s, which is correspondent to the low heat flows in this trench and reflects the character of the leading edge of the subducting South China Sea plate. We notice a very slow Pn velocity anomaly (less than 7.7 km/s) in the eastern sub-basin of the central South China Sea, where is the spreading center of the South China Sea, with the thinnest crust, the highest heat flow and pronounced magnetic anomalies\cite{25,26}. The eastern sub-basin is therefore considered as an extinct mid-oceanic ridge\cite{8}. The very slow Pn velocities show an active uppermost mantle beneath the eastern sub-basin. It indicates that the seafloor spreading is not characterized only by the crustal extension\cite{4}, but also by the upwelling of hot mantle along the pull-apart ridge, which resulted in a thinning or removal of the lithospheric mantle and it is similar to that beneath the Okinawa Trough\cite{10\textasciitilde27}. Surface wave tomography studies also reveal a shallow, thick and oceanic-type asthenospheric mantle beneath the central South China Sea\cite{11,12}. Taken together, the slow Pn velocity and high heat flow suggest that the eastern sub-basin of the South China Sea should be an extinct mantle upwelling center.

Slow Pn velocities of 7.7\textasciitilde7.8 km/s are observed from the northern Philippine, Luzon, eastern Taiwan to the Okinawa Trough. As a result of back-arc extensions, the mantle upwelling and the thinning of the lithosphere were proved by seismic tomography studies in the eastern China seas\cite{10,27}. As a convergent zone between the western Philippine Sea plate and the Eurasian continent, the Luzon Arc has undergone the subduction from east and west directions, which caused intense seismic and volcanic activities and crustal shortening\cite{8}. Low S wave velocities are observed in the lower crust and upper mantle, which is related to magma activities below the volcanoes\cite{28}. All these explain the slow Pn velocities in the northern Philippine and Luzon Arc. In contrast, Pn velocities in the western Philippine Sea are 8.0\textasciitilde8.2 km/s correspondent to fast velocities of oceanic lithospheric mantle. There is a relatively slow velocity zone between the northern and southern fast velocity zones. It is also clear on the S wave velocity images at 80\textasciitilde100 km depths and is explained by a pull-apart ridge of the young central basin of the western Philippine Sea\cite{29,30}.

### 3.2 Anisotropy

Figure 6 shows anisotropy of the Pn velocity in the northeastern South China Sea and adjacent region. The bar indicates fast direction, and the length is proportional to amplitude of anisotropy.

Small anisotropy is observed in southeastern China, which is well correlated with surface wave anisotropy\cite{31}. They reveal less deformation of the lithospheric mantle in this tectonically stable region, and are also consistent with weak seismic activities in southeastern China.

Strong anisotropy is found from the northern South China Sea to the Taiwan Strait. Fast directions are parallel to strikes of the pull-apart basins and major faults in the shallow crust, and they reflect the lithospheric mantle deformation caused by the Mesozoic-Cenozoic pull-apart rifting in the continental margin of the northern South China Sea. Similarly, a shear-wave splitting study in the Taiwan region shows fast SKS wave directions parallel to shallow structures\cite{32}. It reveals an inherited relation between surface geology and tectonic defor-
Fig. 6 Inversion result for Pn anisotropy
The bar indicates the fast Pn direction and length is proportional to the anisotropy amplitude.

formation of uppermost mantle, reflecting the collision of the Philippine Sea plate with the Eurasian continent in the Taiwan region.

Strong anisotropy is observed near along the Ryukyu-Taiwan-Luzon arc zone, with fast directions parallel to the subduction zone, particularly along the Ryukyu, Manila and Philippine Trenches. They are correlated with the strong collisions in the leading edges of the Philippine Sea plate and Eurasian continent. We notice a complicated change of fast directions in the eastern Taiwan. Because a conversion of collision mechanisms between the Philippine Sea plate and the Eurasian continent resulted in a tear of lithosphere in the eastern Taiwan \cite{33}, we infer that the tectonic deformation caused by lithospheric tear is one of major reasons for the complicated change of fast directions in the eastern Taiwan seas.

3.3 Station Delay

Station delay is related to crustal thickness and average velocity in crust. The negative value means a thinner crust and a higher average velocity, and the positive value means a thicker crust and lower average velocity. Fig. 7 shows station delays obtained from the inversion and the crustal thickness based on the global model CRUST 2.0.

Station delays are well correlated with the change of the crustal thickness in the study area. The coast of southeastern China has small station delays, this is because the actual crustal thickness there is about 31∼32 km, very close to that in the reference model. Station delay becomes larger in the inland of southeastern China, and this is consistent with the increase of the crustal thickness from the coast to the inland areas. A large station delay of 1.0 sec is observed in the Taiwan region. Based on the new result from a tomographic study, the crustal thickness of eastern Taiwan is 50∼55 km, due to the shortening caused by the underthrust of the Eurasian continent beneath the Philippine Sea plate \cite{34}. Therefore, the large station delay in the Taiwan region is attributed to an increase of the average crustal thickness. One station in the northern Philippine has a large delay time about 1.0 sec, but delay times in other stations around it are less than or equal to 0.3 sec. Besides, the crustal thickness in the Luzon Arc and northern Philippines is very close to that in the reference model \cite{28,35}. We infer therefore that this large station delay should be excluded from the inversion result.

Fig. 7 Station delays and crustal thickness
(modified from CRUST 2.0 \cite{18})

4 CONCLUSIONS

Pn velocities reveal the features of the uppermost mantle relevant to regional geology and tectonics of the
southeastern South China Sea and adjacent region. The fast Pn velocities in southeastern China reflect a tec-
tonically stable character of the lithospheric mantle; the slow Pn velocity anomalies in the coast of southeastern
China, particularly along the Binhai fault zone, indicate that the fault zone penetrates through the Moho into
the uppermost mantle. The fast Pn velocities in the northern South China Sea and Taiwan Strait show the
character of the lithospheric mantle in the continental shelf. The fast Pn velocities near the Xisha Trough and
adjacent area not only reflect the southward extension of the northern continent, but are also related to the
mantle upwarp caused by the pull-apart rifting beneath the trough. There is no evidence of large-scale thermal
activities in the uppermost mantle of the northern South China Sea. However, a very slow Pn velocity anomaly
is observed in the eastern sub-basin of the South China Sea, which is close to the seafloor spreading center
with magnetic anomalies. It suggests a strong thinning or removal of lithospheric mantle, therefore, this region
should be an extinct mantle upwelling center. The slow Pn velocities from the eastern Taiwan-Luzon-northern
Philippine are closely related to the seismic, volcanic and magma activities along the subduction zones between
the western Philippine Sea plate and the Eurasian continent.

Pn anisotropy also reflects the stress distribution of regional tectonics and the deformation character
within lithospheric mantle. Small anisotropy in southeastern China reveals less deformation in the lithospheric
mantle. Fast directions parallel to shallow structures of the northern continental margin of the South China Sea
reflect a fossil deformation in the lithospheric mantle, produced by the Mesozoic-Cenozoic rifting and shearing.
Strong anisotropy is also observed along the Ryukyu-Taiwan-Luzon arc zone. Fast directions aligned with
oceanic trenches indicate strong deformation of the lithospheric mantle in the leading edges of the subducting
Philippine Sea plate and Eurasian continent. The changes of the fast directions in the eastern Taiwan seas are
probably related to the conversion of the collision mechanism between the Philippine Sea plate and the Eurasian
continent, and to the tear of the lithosphere caused by this dynamic process.

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