Seismic imaging of oceanic crust across the northwestern subbasin, South China Sea

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***Abstract*-Located at the northwestern part of the South China Sea(SCS) among the east subbasin, the Zhongsha Islands(Maccelesfield Bank), and the Xisha Islands(Paracel), the NW subbasin is the smallest ocean basin in all the three subbasins of SCS. It presents all major stages from rifting in the late Oligocene to initial seafloor spreading in the mid-Miocene, thus provides an ideal place to study the rifting and initial seafloor spreading process in great detail. In autumn 2006, a wide angle seismic profile has been acquired by the SIO, SOA of China, which starts from Pearl River Mouth Basin, goes across the NW subbasin and the Zhongsha Islands, ends at east subbasin of South China Sea, 484km in length. The refraction/reflection data were recorded by 13 three components Ocean Bottom Seismometers (OBS) and seismic energy was provided by 22 air-gun array with different volumes with whole volume of 5160inch^3. A detailed velocity model was obtained by using an interactive trial-and-error 2D ray-tracing method. Data inversion and analysis show that, the crust thickness under the continental slope decreases from 21km to 11km, the crust thickness of the NW subbasin is about 7.7km, and the moho depth ascends from 21km to 11km. The crust of the NW subbasin similar to the east subbasin in structure is confirmed to be oceanic crust, with thicker layer 1(sedimentary layer) and thinner layer 2 especially obvious in east subbasin, which is some different from typical oceanic crust structure. The tectonic geometry and velocity structure of the NW subbasin and its margins on both sides shows symmetrical and conjugate and indicates pure shear mode in continental margin rifting mechanism. We don't find clear seismic signals from high velocity layer under the lower crust of the continental margin in the northern of the NW subbasin, which supplies new evidence for the viewpoint that western part of the northern continental margin of South China Sea is non-volcano crust. ***

***Key words*-wide angle seismic, oceanic crust, northwestern subbasin, continental margin rifting**

I. INTRODUCTION

The South China Sea is a unique basin with special evolution history among western Pacific marginal seas. Oceanic crust and magnetic anomaly zone has been approved to be existed in the eastern subbasin and the SW subbasin in three main subbasins which formed South China Sea[1~7], but there is no obvious magnetic anomaly zone found in the NW subbasin[8]. Though many scholars indicate that the NW subbasin is a small oceanic basin with seafloor spreading happened in their hypothesis, there is less evidence to reveal the evolution dynamics of the NW subbasin with its two sides, and to approve the crust nature of the NW continental margin, SCS, and to illustrate the relationship between the NW subbasin and the SW subbasin.

Seismic technology, especially using Ocean Bottom Seismometer(OBS) in profile investigation is efficient tools to imply deep crust structure[9]. In 1990s, multiple wide angle seismic or deep seismic investigation profile have been acquired[10,11], among them there are two OBS profiles[12,13] and on ESP profile[6,14] in the NW subbasin(Fig. 1). In the three profiles, ESP-W profile and OBH96 profile are located in the Xisha Trough zone, OBS93 is located in eastern subbasin, but no profile goes cross the NW Subbasin directly. To reveal the crust structure of the NW subbasin and get the velocity information, thus support the rifting mechanism and seafloor spreading course of the NW subbasin, the Second Institute of Oceanography, State Ocean Administration(SOASIO) has carried out a wide angle seismic experiment in the middle-northern SCS during Autumn to October, 2006, three profiles have been acquired[11,15], and profile OBS2006-1 starts from northern continental shelf, goes cross the NW subbasin and extends to Zhangsha Islands and the eastern subbasin, which supply precious data for this study.

II. DATA ACQUISITION AND DATA PROCESSING

A. Data Acquisition

In autumn, 2006, SOASIO conducted a surveyed in the middle-northern SCS with the R/V Fendou Seven, three new high-quality wide angle reflection/refraction profiles were acquired. Seismic energy was provided by 22 air-gun array with different volumes with whole volume of 5160 inch^3. The shot time and distance intervals for OBS were set as 90 seconds and 200 m, respectively. 14 Sedis IV type OBSs[16,17] were deployed and 13 OBSs were recovered along the NW-SE profile OBS2006-1 with a total length of 484 km, the lost OBS was No.9 station.

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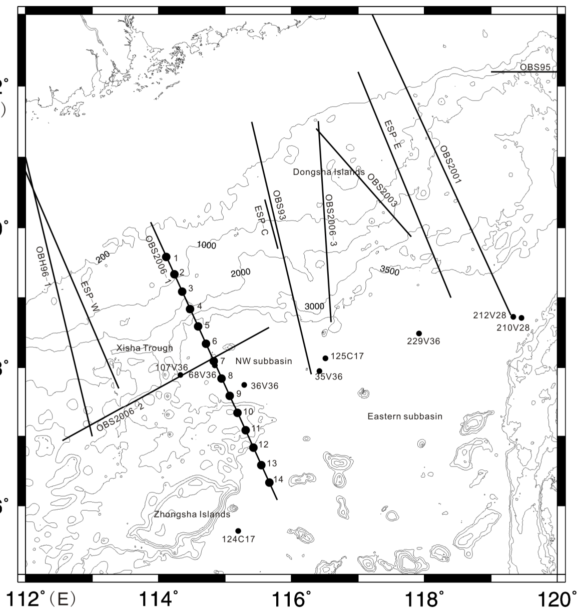

Fig 1 The location of profile OBS2006-1, distribution of OBS stations and other deep seismic profiles distributed in the northern margin, SCS(the black lines are OBS lines and ESP lines, the bigger black dots are the OBS stations of this paper, the smaller ones are sonobuoy stations .)

With a three components seismometer is mounted on a universal frame, the Sedis IV type OBS also has one hydrophone, and the base frequency of the seismometer is 4.5 Hz, frequency band 2~100 Hz. The seismic signals are converted by 16 bit A/D converter and recorded to two 8G flash cards. Cause the affection of sea flow etc, OBS location may be departure from the deploying position while it falls freely down to the seafloor, thus we can got the real position of each OBS from calibration for the direct wave[18].

B. OBS Data Processing

The OBS data process includes shot time calibration, shot coordinate localized, OBS position correction and OBS recording time drift correction. Firstly, revise the shot time recorded by the ship with the precise shot time recorded by seismometer on the deck, taking into account the wave filter delay. According to the gunshot coordinate 's GPS navigation data, confirm a line as profile using the least square method, projects all gunshot and OBS station to the profile and get the coordinates of gunshots and OBS positions on the profile, then calculate the offset. Get every OBS's reduced time profile (reduced velocity is 6km/s) according to the corrected gunshot and offset. The band filter frequency for the OBS is 4-30Hz. Determine the seafloor under the profile using the depth data acquired by the cruise and get the OBS vertical coordinates. Taking the time drift of the recorder as a linear function, calculate the drift increment with the start time, end time and whole drift time, then add the drift increment to the every channel of the reduced time profile. By Comparing the calculated time of direct water wave near the small offset with the reduced time profile, calibrate the OBS coordinate to get good fitness of them, and finally determine the OBSs' locations. From the reduced time profile (OBS1 as an example, Fig. 2) we can see that the max offset is more than 110km, and direct wave from ocean bottom(P_{1P}), reflective wave of sediment layer one(P_{2P}), refractive wave of the crystallized basement(Pg), reflective wave of Moho surface(PmP) and refractive wave under the Moho surface(Pn) are contained in the seismic phases.

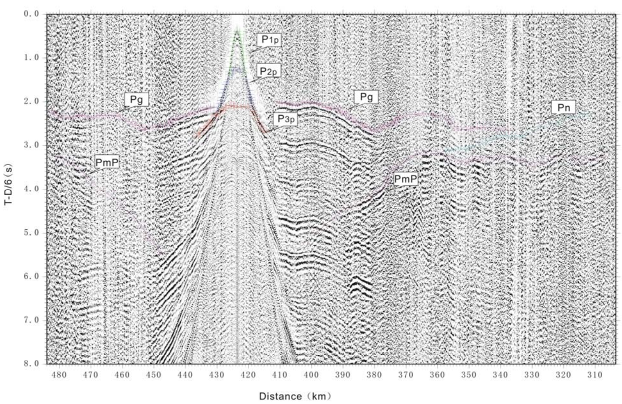

Fig 2 OBS1 seismic phases map(P_{1p} represents direct wave of seafloor,P_{2P} represents reflective wave of sedimentation layer one, P_{3P} represents reflective wave of sedimentation layer two, Pg represents refraction wave of crystallization basement, PmP represents reflection wave of Moho surface, Pn represents refraction wave under Moho surface, reduced velocity is 6.0km/s)

C. Using of Multi-channel Seismic Profile

Fig. 3 is a multi-channel seismic profile acquired by joint cruise of SIOSOA and Federal German Geoscience and Natural Resource Institute with German ship R/V SONNE in 1987 in the South China Sea[19], OBS2006-1 profile are designed to go along it. The multi-channel seismic profile shows the tectonic characteristic of the NW subbasin clearly. Thick sediment coverage can be seen in the ocean basin, three layers are divided which represents late Oligocene rifting period, early Miocene post rifting period and middle Miocene thermal subsidence period respectively, and the two interfaces represent 23.5Ma and 16.5Ma. The sediment basement is clear, the two sides of the oceanic basin is made up of a serious of dustpan-like subsidence grabens, and there are a serious of ladder-like normal fault inclined to the oceanic basin in the continental slope and oceanic basin intersection part. The continental rifting activity continued from onset of seafloor spreading to early Miocene post spreading period. Entering the thermal subsidence period, the affect of the fault weaken, and sedimentation is mainly warp around in plane. The basement in the middle of oceanic basin which uplift obviously is intrusive magma material. In addition, the Moho reflection is clear and symmetry in the NW subbasin, but the basement velocity is different in two sides, while the northern part near the continental is higher than the part near the Zhongsha Islands. The tectonic characteristic of the multi-channel profile supplies evidences for the research of the tectonic evolution of continental margin and oceanic basin, also for the building initial model of the OBS profile.

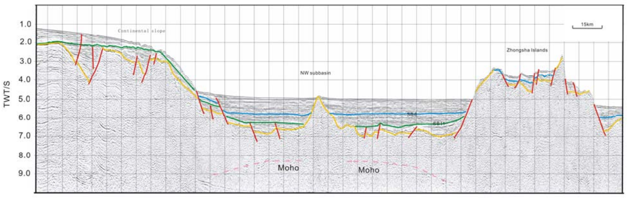

Fig 3 Multi-channel seismic profile SO49-18

III. INVERSION OF CRUST STRUCTURE

The inversion of the wide angle seismic transact conducts using the ray tracing software Warrpi[20]. Firstly using the 2D ray tracing method calculate the theoretical travel time, and employ trial-and-error method to the fit all kinds of the seismic phases picked from the vertical component records to construct the P wave velocity model. The principle in the inversion of the velocity model is only use the layer with identified seismic phases and be independent of automatic inversion to avoid adding presumed interfaces in the model which has better fitness but no identified phases.

According to the previous MCS profile, regional geology, first arrival tomography modeling and seismic phases identified from observed data, we construct the velocity model with 5 interfaces and 6 layers, including sea water, three sediment layers, crust layer and upper mantle. The inner interface(dashed line) in the crust is added after inversion. The inversion is carried out from the uppermost interface downward to Moho surface one by one using ray-tracing method to calculate travel time and trial-and-error method to fit the data. The upper three interfaces are confirmed by MCS data and the seismic phases are fitted by adjusting the velocity in landscape and vertical directions. The crystalline basement, velocity distribution in the crust and Moho geometry are the key point of the work.

The records of the thirteen OBS show that the dominant seismic phase is Pg refracted beneath crystalline as well as Pn refracted from Moho except for other small offset reflective and refractive phases from seafloor and sediment layers. Phase Pg covers the whole model and overlaps in many parts and phase Pn covers most part of the model. Since the shallow layers introduced from previous MCS profile are reliable and enough various seismic phases such as Pg and Pn are identified from the observed data, the final true velocity model can be got by giving all phases the best fit with 2-D ray tracing method and trial-and-error method. After adjusting the model for many times and fit the calculated curves of seismic phases with the observed ones time after time, we obtain the final velocity model(Fig. 4).

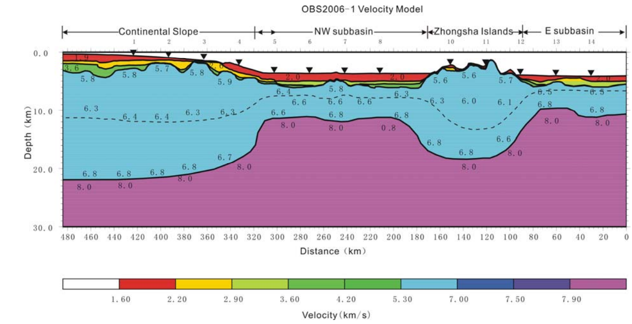

Fig.4 Crust structure and velocity (Vp)distribution along profile OBS2006-1 ,VE=5

The ray tracing and curve fitting of Pg in OBS4 section(Fig 5) ensure perfect modeling of the crystalline basement 180km wide in the model, including most part of the continental slope and northern part of the NW subbasin. About 30km PmP and 40km Pn phases are also recorded in the northern part of NW subbasin by OBS4 section. In both sides of OBS10 at the northern side of the Zhongsha Islands the phases Pg and PmP are fitted well(Fig. 6). Here only two OBS stations are illustrated to show the situation of inversion because of their representative locations, in fact seismic phases picked in all thirteen OBS stations are fitted well enough. For instance, the OBS1 station mentioned before whose Pg phase also controls the whole continental slope basement geometry and has good constraint on the Moho surface(Fig 2). Generally speaking, the final velocity model is relatively reliable and objective because of good constraining from the various of overlapping phases in all thirteen OBS stations.

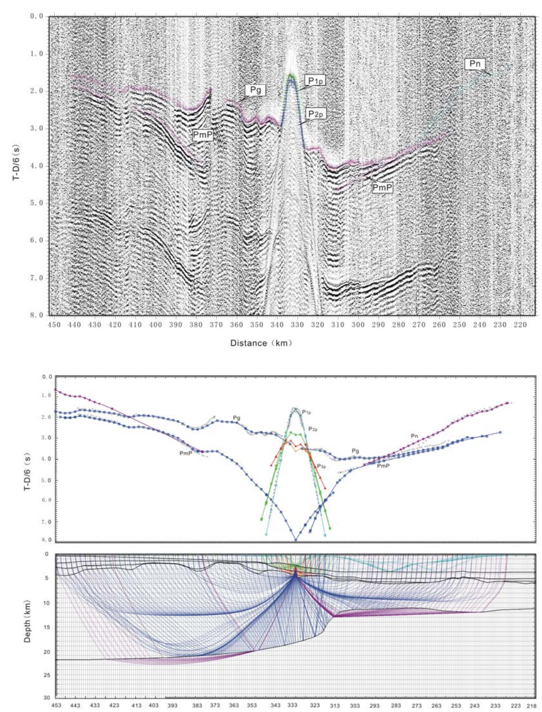

Fig 5 OBS4 seismic phases and ray tracing map

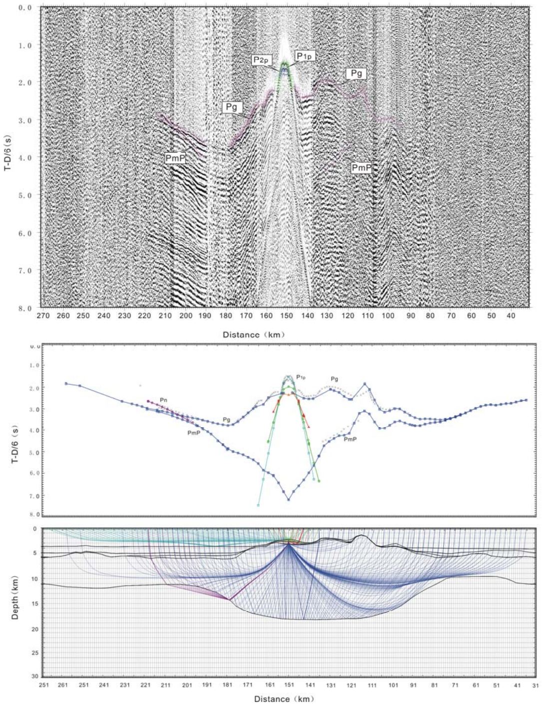

Fig 6 OBS10 seismic phases and ray tracing map

IV. Crust Model

The NW-SE orientation wide angle profile OBS2006-1 starts from the Zhujiang Mouth Basin in the north, goes through the Zhu II subsidence and into the NW subbasin, then it goes across the eastern part of the Zhongsha Islands and ends at the eastern subbasin. The total length of the profile is 484km, water depth ranges from 340m to 4167m. The characteristic of the inversion model is the Moho depth under the continental slope is ca. 18~22km, the crust at the middle part of the NW subbasin is pull apart obviously and the crystalline basement is uplift, while the corresponding Moho surface subsides a little whose depth is ca. 12km. The Moho depth under Zhongsha Islands is ca. 18km, and crust velocity distribution is similar to that of the northern margin. In the below, the structure characteristic of the crust in the model will be depicted in the order of the continental slope(water depth 0.3~3.5km), NW subbasin(water depth>3.5km), Zhongsha Islands(water depth 2～3.5km) and the eastern subbasin(water depth >3.5km).

A. Continental Slope(model distance of 320～484km)

The crust structure under the continental slope is mainly constrained by four OBS stations, OBS1,OBS2,OBS3 and OBS4. Three sediment layers are contained in the continental slope, and the velocity of sediment layer 1 is ca.1.9km/s which thickness is 0~1.3km, the velocity of sediment layer 2 is ca. 2.6km/s which thickness is 0~1.6km, the velocity of sediment layer 3 is ca. 3.6km/s which thickness is 0~1.5km. The total thickness of the sediment is ca. 0.5~4.1km and the average thickness is ca. 2.1km. The crust velocity range is 5.6-6.8km/s, and the crust thickness (including the sediment layer) decreases from the continent to the sea which ranges from 13.2 to 21.5km, the Moho depth varies from deep to shallow, 21.9km under the OBS1 station to ca. 18.5km under the OBS4 station.

B. NW subbasin(model distance of 170～320km)

The crust structure under the NW subbasin is constrained mainly by four OBS stations, OBS5, OBS6, OBS7 and OBS8. From the model three sediment layers exist in the NW subbasin, and the velocity of sediment layer 1 is ca. 2.0km/s, a little larger than that in the continental slope, its thickness is 1.0~1.3km, the velocity of sediment layer2 is ca. 2.9km/s which thickness is 0~0.9km, the velocity of sediment layer 3 is 3.6km/s which thickness is very thin, 0~0.6km, and disappear in the middle of the basin. The total thickness of the sediment is ca. 0.6~2.6km and the average thickness is ca. 2km. The crust velocity ranges from 5.4-7.0km/s and the crust thickness decreases from continental slope to the basin then increases from the basin to the Zhngsha Islands which thickness ranges from 7.7 to 13.2km, the Moho surface comes up from the continental slope to the basin which is a little subsidence in the middle of the basin, and then goes down from the basin to the Zhongsha Islands, the Moho depth is 11.8 under the OBS5, 11.2km under the OBS6, 12.2 under the OBS7, 11.8km under the OBS8. The crust thickness is thicker in the middle and thinner at both sides with buried volcano in the middle, and the crust structure on the both side is symmetry.

C. Zhongsha Islands(model distance of 90～170km)

The crust structure of the Zhongsha Islands is constrained by three OBS stations,OBS10,OBS11 and OBS12. From the model we can see that the sediment in the Zhongsha Islands is very thin and mainly comprises two sediment layers, the velocity of sediment layer 1 is 1.9km/s which thickness is 0~0.4km, the velocity of sediment layer 2 is 2.7km/s which thickness is 0~0.6km. The crust velocity ranges from 5.5 to 6.9km/s, and the crust thickness ranges from 9.5 to 16.8km, the Moho depth becomes deeper and then shallower which is ca.18.4km under the OBS10 to 18.1km under OBS11 and 12.9km under OBS12.

D. Western Part of Eastern Subbasin(model distance<90km)

The crust structure under the western part of the eastern subbasin is mainly constrained by two OBS stations, OBS13 and OBS14. Three sediment layers are contained in the eastern subbasin, and the velocity of the sediment layer 1 is 2.0km/s which thickness is 0.3~1.1km, the velocity of sediment layer 2 is 2.9km/s which thickness is 0~1.3 km, the velocity of sediment layer 3 is 3.6km/s which thickness is 0~0.5 km and is similar to that of the NW subbasin. The total sediment thickness ranges from 0.9 to 2km and average thickness is 1.6km. The crust velocity ranges from 6.3 to 6.8 km/s, and the crust thickness increases from NW to SE which thickness is 5.6~9.5km, the Moho depth becomes shallower and then deeper which is 9.7km under the OBS13 to 11.2km under the OBS14. Both the crust thickness and Moho depth are smaller in the eastern subbasin than in the NW subbasin.

V. Discussion and Conclusion

A. Rifting Mechanism in the NW Subbasin Continental Margin

There are three modes about the pulling apart and rifting of the continental margin in generally, the pure shear mode[21], simple shear mode[22] and layered shear mode[23]. Different viewpoints exist on the rifting mode of the eastern subbasin, such as simple shear mode[24,25], pure shear mode[26], layered shear mode[27] and simple shear in early stage and pure shear in later stage[28], etc, but fewer dissertation on the NW subbasin. The OBS2006-1 profile goes across the NW subbasin and its both sides continental margin which supplies conditions for the study on the analysis of basin conjugate characteristic and dynamic mechanism.

From the topography and relief we can see that the northern margin of NW subbasin is an arc concave to the north while the southern margin is an arc bulgy to the north, which seems that clearly conjugate relationship between the two margins. From the MCS transect we can see that the Neozoic distortion in the NW subbasin continental margin is mainly SE dip normal fault, graben, half graben in the northern continental margin, and NW dip normal fault, graben and half graben in the southern side Zhongsha Islands, symmetry distributed faults also exist in the middle of the basin which dips are opposite to each other, all these above are fitted the pure shear model. From crust structure of the continental margin in both sides we can see that the thickest crust of the Zhongsha Islands in the southern side of the NW subbasin is about 16.8km, and can be divided into upper crust with velocity 5.3~6.5km/s and lower crust with velocity 6.5~6.8km/s, which is similar with the velocity structure of the northern continental side, we can infer that there is conjugate relationship between the two sides and the crust nature of the Zhongsha Islands is transition crust. There is thicker sediment covered in the northern continental margin which consist mainly three sediment layers, while the sediment in the Zhongsha Islands is very thin for the reasons of uplift and volcano, etc, and in some area sediment disappear.

From the crust structure of the basin we can see that the Moho surface under the basin becomes deeper smoothly from two sides 11km to the middle 12km, the geometry of both sides are symmetry. The thickness of the crust decreases from the 21km in the continental slope to the 7.7km in the basin, strong thinning happened. Synthesis the above, we suggest that the rifting mode of the NW subbasin is pure-shear mode.

B. Non-volcano Crust in the NW Subbasin Continental Margin

Until now, several deep seismic profiles which contained the ocean continental transition information have been acquired, because of the complexity of the evolution of SCS, different characteristics of these profiles reflect different tectonic evolution information respectively. High velocity layer(HVL) was found in the lower continental slope of the ESP-C[6] transect near the Dongsha Islands of the NE SCS, which was confirmed of 5~8km thickness HVL by the OBS93 transect coincide with the ESP-C transect, while the ESP-E[6] transect in the East and OBS2001[29] also found HVL about0~5km thick, and HVL was also found in the transect OBS2006-3[30] . In the NW part of the SCS, HVL was found existed in the ESP-W, and it seemed that the northern part of SCS were all volcano margin, but after that OBH96 transect adjacent to it found no HVL which explained this was caused by poor quality data of ESP transect and the non-reliability of one dimension simulation[12]. Therefore, whether there is HVL existed in the western part of the northern margin SCS is unconfirmed because there is no more control transect of curst structure in the large part of area between ESP-C and ESP-W, and no clear conclusion can be given in the discussion of the crust nature in western part of the northern SCS. The result of OBS2006-1 which confirms that non HVL exist in the lower crust proves the non-volcano crust nature in the western part of the northern continental margin of the SCS, and reinforcements the viewpoint that the crust nature is volcano type in the eastern part of northern margin SCS and non-volcano type in the western part of the northern margin SCS. Meanwhile the location of OBS2006-1 suggests that the continental margin nature is non-volcano in the western side of NW subbasin, and supplies important information for dividing the limit line of crust nature.

C. Velocity Structure Analysis in the NW Subbasin

According to the OBS velocity structure in the NW subbasin, the crust is divided into upper crust(oceanic layer 2) and lower crust(oceanic layer 3) with the velocity 6.5km/s, the velocity of the upper crust in the basin is 5.4~6.5km/s which thickness is ca. 1.1~2.9km(1.7km in average),corresponding to typical oceanic crust[31] layer 2, and the velocity of lower crust is 6.5~7.0km/s which thickness is 3.4~4.7km(4.0km in average), corresponding to oceanic crust layer 3, and there is a clear boundary line between layer 2 and layer 3 and velocity layer 6.3~6.5km/s is almost lost at the bottom of layer 2. The sediment thickness in the NW subbasin is 2km in average, the crust thickness is ca. 7.7km, Moho depth is ca. 11km, which is obviously oceanic crust nature. And the possibility of the basin is in the continental rifting period and there are continental crust and oceanic crust blending together or relict continental crust is eliminated. Compared with the transect OBS93 which OBS14 and OBS15 stations are located in the eastern subbasin, the velocity distribution characteristic of the layer 2 and layer 3 are similar to that of transect OBSS2006-1,and both are lack of the velocity layer 6.3~6.5km/s. The thickness of layer 2 in the eastern subbasin is much thinner than in the NW subbasin, but the thickness of layer 3 is similar. The analysis on the sonobuoy velocity profile in the NW subbasin and eastern subbasin indicates that the conformity of the velocity structure of layer 2 and layer 3 is not good, the thickness variation is much large and in general the layer 3 is thought to be thinned greatly. But according to our study on the transect OBS2006-1,the thickness of layer 3 is stable which is in the range of 4~5km and close to that of typical oceanic layer 3 ca. 5km, no matter in the NW subbasin or in the eastern subbasin. The oceanic layer 2 has the phenomenon of thinner which is 1.8km in the NW subbasin and 0.6km in the eastern subbasin, the thinner of layer 2 in the eastern subbasin is much more obviously. Further study shows that there is difference between the two sides of the basin in velocity and thickness of the layer 2，and the velocity in the Zhongsha Islands side of the basin is ca. 0.1km/s lower than that in the northern continental margin side which indicates the unsymmetrical basaltic magma outpouring of the layer 2, and more magma in the southern side, less in the northern side.

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