PROGRESS IN NATURAL SCIENCE Vol. 13, No. 7, July 2003

REVIEW ARTICLE

Recent progress of deep seismic experiments and studies of crustal structure in northern South China Sea*

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Received December 25, 2002; revised February 9, 2003

Abstract The South China Sea (SCS) is one of the largest marginal seas in the western Pacific. Its northern part has the features of a passive continental margin. The studies of deep crustal structure in this area are very important for understanding the tectonic nature, evolution history, basin formation of the northern margin, and the origin of the SCS. In the past decades, the deep seismic experiments of crustal studies in the northern SCS have gone through three stages, namely the sonobuoy, two-ship Expanding Spread Profile (ESP), and Ocean Bottom Hydrophone/Seismometer (OBH/OBS). Along the continental slope, the sonobuoy experiments provided useful information about the velocity structure of the upper crust, while the ESP data recorded for the first time the seismic signals from deep crustal structure and Moho interface. And the OBH/OBS profiles revealed the crustal structure in much greater detail. This paper first gives a brief historical review of these deep seismic experiments and studies, then a summary of the latest progress and important research results. The remaining problems and suggestions for further research work are presented as conclusive remarks.

Keywords: **northern South China Sea, crustal structure, deep seismic experiments, passive continental margins.**

The South China Sea (SCS), one of the largest marginal seas in the world, is located in the joining areas between the Euroasian, Indian-Australian and Pacific super plates. It has a complex tectonic pattern and geophysical field. The northern part of the SCS possesses the features of a passive continental margin since late Cretaceous. It has a close genetic relation with the formation and spreading of the SCS. Since the 1960s, the marine geologists, both at home and abroad, have paid much attention to the studies of deep structure and tectonic nature in the northern part of the SCS. With the continuous improvement of the observational instruments and conditions, and the accumulation of our geological knowledge, the deep seismic experiments and the crustal structure studies in the northern SCS have experienced the process from shallow to deep, from gross to detailed, and from understanding to re-understanding. Especially after the 1990s, the OBH/OBS technique became well established and many OBH/OBS profiles were recorded in the northern SCS (Fig. 1). A large amount of high quality deep seismic data was acquired and a lot of new knowledge was obtained by data processing and modeling. These new data and knowledge have further advanced the studies of crustal structure and tectonic features in the northern SCS[1~6]. In this paper, the history of deep seismic experiments and studies in the northern SCS is reviewed first and the penetrating/imaging ability of various seismic methods is discussed briefly. Then the OBH/OBS experiments in recent years and related research results are presented. The geological interpretation and tectonic significance of these new research results are investigated and discussed. Finally remaining problems and constructive suggestions for further research work are pointed out.

1 Sonobuoy experiments

The studies of the geophysical field and crustal structure in the northern SCS[8,9] began in the 1960s, mainly covering gravity, magnetic, echo sounding and single channel seismic investigations. From the late 1970s to the early 1980s, a large number of Multi Channel Seismic (MCS) surveys were carried out by the Chinese and foreign oil companies and the ex-Ministry of Geology and Mineral

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* Supported by the Chinese Academy of Sciences (Grant Nos. KZCX2-209 and KZ952-B1-406), the National Natural Science Foundation of China (Grant Nos. 4000161958, 49804005, 49504055, 40276015 and 40204006) and the Chinese Ministry of Science and Technology (Grant No. G2000046701)

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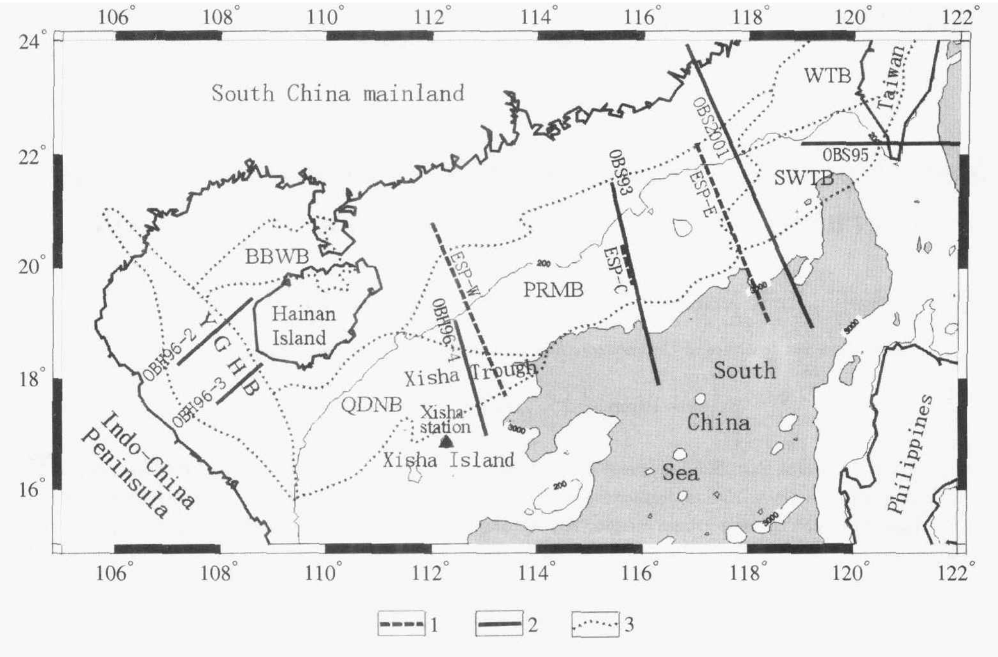

Fig. 1. The oil-gas basins and the deep seismic profiles in northern South China Sea. 1, Two-ship ESP transects; 2, OBH/OBS profiles; 3, oil-gas basin boundaries[7]. YGHB, Yinggehai Basin; BBWB, Beibuwan Basin; QDNB, Qiongdongnan Basin; PRMB, Pearl River Mouth Basin; SWTB, Southwest Taiwan Basin; WTB, West Taiwan Basin.

Resources (MGMR). Many research results were published[10,11]. However, the MCS method normally can only explore to a depth of several thousand meters. And its investigation objects are mainly the detailed structure of the sedimentary layers inside the oil and gas basins. In order to study the deep structure characteristics beneath the sedimentary basement, the ex-MGMR of China and the Lamont-Doherty Earth Observatory (LDEO) of USA cooperated and carried out sonobuoy refraction seismic experiments[12,13]. The research results show that the abysmal plain in the northern SCS has an oceanic crust, which possesses the typical three-layer structure. The Moho depth is 8 ~ 12 km and the crustal thickness is 5 ~ 9 km. However, recording at sea surface, sonobuoy was easily affected by bad weather and sea conditions. The maximum observational distance of the sonobuoy is only 40 km[14]. It is, therefore, difficult to probe the deep structure along the continental shelf and slope, which somewhat limits the deep crustal studies in the northern SCS.

2 Two-ship ESP experiments

In 1985, the ex-MGMR and LDEO started a new cooperation and carried out two-ship ESP experiments, which led to a new and fruitful round of deep seismic survey and crustal studies in the northern SCS[15,16]. This Sino-US cooperation completed three NNW-SSE main transects crossing the northern margin. These three transects (ESP-E, ESP-C and ESP-W), parallel to and apart from each other in roughly equal distance, start from the offshore continental shelf and end near the northern edge of the abysmal basin (Fig. 1). Perpendicular to the transects, most of the total 19 ESPs reach the depths of Moho. The modeling results show that along the Eastern Transect (ESP-E), the Moho depth is 30 km in the continental shelf and gradually becomes shallower to 11 km toward the oceanic basin. A continuous high velocity layer (HVL, $V_p > 7.0$ km/s) with a maximum thickness of 17 km is found in the lower crust. Along the Central Transect (ESP-C), there are only 3 ESPs and the Moho depths are 27 ~ 25 km, which also become shallower southward. Along the Western Transect, the Moho depths are mainly 30 ~ 26 km, but shallower in two places: one is the Zhu-3 Depression of PRMB where the Moho depth is 23 ~ 24 km and the other is the Xisha Trough where the Moho depth is about 17 km. Sparse and thin HVLs are suggested in the lower crust. The crustal models of the three transects all show a very thin upper crust, with a minimum thickness of only 1 ~ 2 km. Only the ESP17 indicates a 16-km-thick upper crust in the southern flank of Xisha Trough. These experiments and their results provided for the first time the velocity information about the deep crust along the northern margin of the SCS and greatly pushed forward the studies of the deep structure and tectonic evolution of this area[17~20]. However, the ESP method also has some limitations. For example, the deep seismic signals are relatively weak because they have to travel through the water layer twice. The ESP requires in strict sense 1-D structure, a condition seldom met on the continental margins. Therefore, the structure models along the main transects are coarse with relatively large error bars. Moreover, the two-ship operation at sea for the ESP experiments is logically more expensive and more complicated.

3 OBH/OBS experiments

From the 1990s, the OBH/OBS technique became increasingly mature and popular in the world. This technique puts seismic receiver, either a hydropone (OBH) or a seismometer (OBS) with single or multi components, onto the ocean bottom, thus dramatically reduces the influence of the weather and sea condition, and greatly increases the coupling with the earth media. With lower ambient noise and larger airgun array, clearer, farther and deeper seismic signals can be detected. In the same period, South China Sea Institute of Oceanology (SCSIO) of the Chinese Academy of Sciences (CAS) and Taiwan Ocean University (TOU) carried out several OBH/OBS experiments in cooperation with western research institutes or universities, initiating a new round of deep crustal studies in the northern SCS. The following subsections summarize these OBH/OBS experiments according to different regions and stages.

3.1 Northwestern SCS

In 1996, SCSIO of CAS and the Research Center for Marine Geosciences (GEOMAR) of Germany collaborated and completed three OBH profiles in the northwestern SCS using airgun sources. Among them, the OBH96-2 and OBH96-3 were located in the YGHB and the OBH96-3 crossed the Xisha Trough (Fig. 1). Xia et al.[1] and Wu et al.[21], with the OBH data, studied the sedimentary layer velocity structure inside the basin, and discussed the relations between the velocity structure and the oil-gas formation. They discovered the existence of a low velocity zone (LVZ) and investigated the buried depths, distribution areas and the formation mechanism of the LVZ. Because of the existence of the LVZ, the very thick sedimentary layer, and the noises caused by the intensive fishing activities, most of the OBHs did not detect the seismic signals from the basement. On the other hand, the OBHs across the Xisha Trough recorded many deep seismic signals. The Pg, Pn and PmP phases were recognized after the data processing and analysis[5,22]. A 2-D velocity structure model across the Xisha Trough (Fig. 2) was obtained by using ray-tracing, travel-time modeling and amplitude comparison. This structure model shows that the Moho is the shallowest in the center of the trough and the Moho depth is only about 15 km, which increases gradually toward both sides of the trough. There is a significant velocity jumps on the Moho interface, where the P-wave velocity increases from 6.8 km/s to 8.0 km/s. A HVL is not seen in the lower crust. The P-wave velocity increases gradually from 5.5~5.6 km/s to 6.8 km/s from the top to the bottom of the crystal crust. A mid-crust velocity interface is not discovered and the 6.4 km/s isoline divides the crust into the upper and lower crust. The crustal thickness is 8 km in the middle of the trough and increases gradually to more than 25 km on both sides. The sedimentary basement interface has a complex shape, on which the hosts and half-grabens are developed. But the overall tendency still shows that the sedimentary layers are thicker in the middle and thinner on both sides. The crustal structure is distributed roughly in a symmetric fashion on both sides of the trough. Based on the above velocity structure model, Shi et al.[6] first modeled the density structure using the satellite gravity data along the profile, then calculated the lithosphere temperature field and the thermal structure with the neighbor heat flow data by applying a 2-D numerical solution of the steady-state heat conduction equation (Fig. 3). They also estimated the lithosphere rheological structure according to the petrological mechanical properties and temperature-pressure conditions. These results show that the density of the upper crust in the middle of Xisha Trough is lower than both sides. The bottom of the "thermal" lithosphere is 54 km deep, defined by the solid line of basalt dry solidus, i.e. $T = (1050 + 3z)$ ℃, where z is the depth in km. It becomes deeper toward both sides, 70 km southward and 76 km northward. The heat flow contribution from the crust is less than that from the mantle, which means that the sea bottom heat flow is mainly from the deep upper mantle. The mantle heat flow is the highest in the central part of the trough. The rheological structure has the characteristics of vertical stratification and lateral variations, and the ductile layer becomes thicker while the brittle layer becomes thinner from the center to both sides of the trough, showing that the center has a larger rheological strength. The lower boundary of the brittle layer in the uppermost mantle is buried at a depth of about 26 km around the isotherm of 650 ℃.

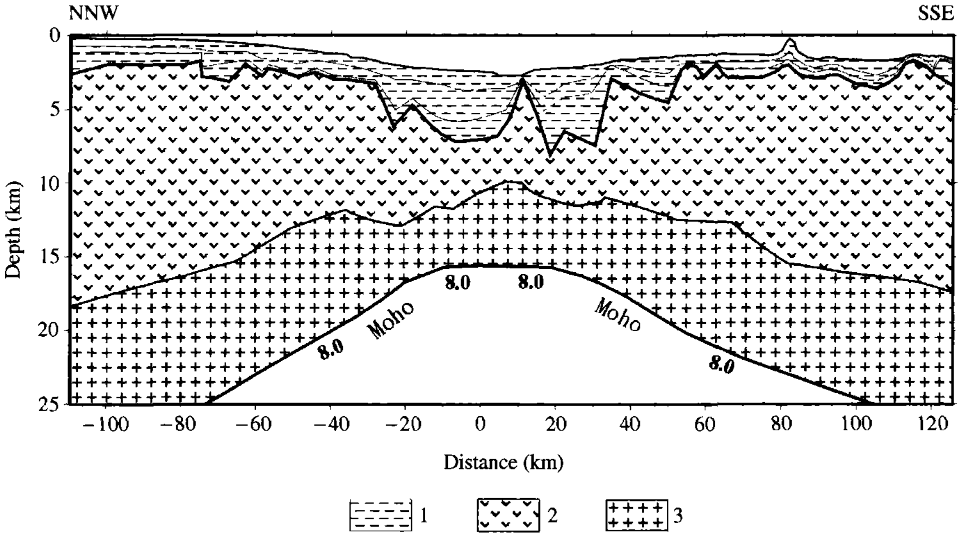

Fig. 2. Crustal structure along the Xisha Trough profile. Modified from Ref. [5], numbers in the figure indicate P-wave velocity (km/s). 1, Sedimentary layer; 2, upper crust (V_p<6.4 km/s); 3, normal lower crust (6.4 km/s< V_p<7.0 km/s).

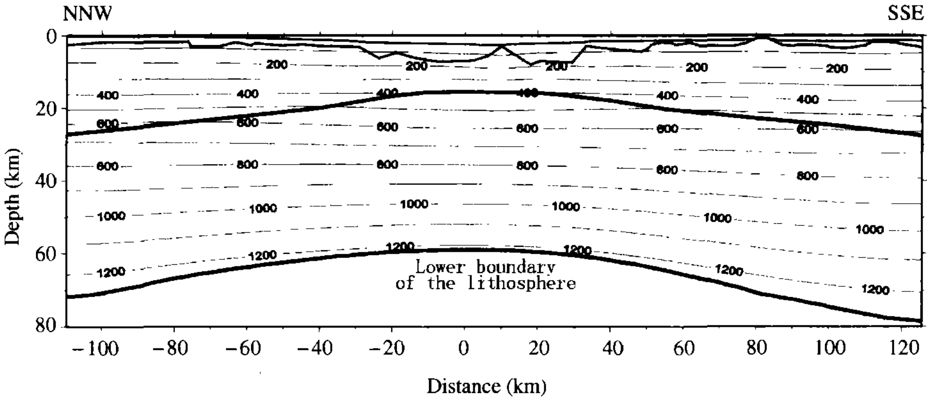

Fig. 3. Lithospheric thermal structure along the Xisha Trough profile. Modified from Ref. [6], numbers in the figure indicate temperature (℃).

3.2 Central PRMB

In 1993, SCSIO of CAS and Tokyo University of Japan worked together and carried out an OBS profile in the middle segment of the northern margin of SCS (Fig. 1). This profile (OBS93), using both airgun and explosive as the seismic sources, transversely crosses the central part of PRMB. The deep seismic phases along the profile are rather clear. There is even a seismic phase coming from uppermost mantle[4]. The three component OBS records also show converted S-wave from sedimentary basement[25]. The crustal structure model (Fig. 4), obtained by seismic phases analyzing and ray-tracing, shows that the crustal thickness along the profile is 22 km in the continental shelf and thins to 8 km in the ocean basin areas. The sedimentary layer is as thick as 5 km in the upper continental slope. The upper crustal thickness is 8 ~ 10 km and there is a HVL in the lower crust with an average thickness of 3 ~ 5 km. Shi et al.[3] calculated the thermal and rheological structure and the results show that the "thermal" lithosphere is as thick as 96 km in the continental shelf areas along the northern part of the profile. It becomes thinner southward in the continental slope and thins to about 62 km in the oceanic crust areas. The lithospheric rheological structure changes gradually from north to south from a 4-layer structure of brittle, ductile, brittle and ductile to a 2-layer structure of brittle and ductile.

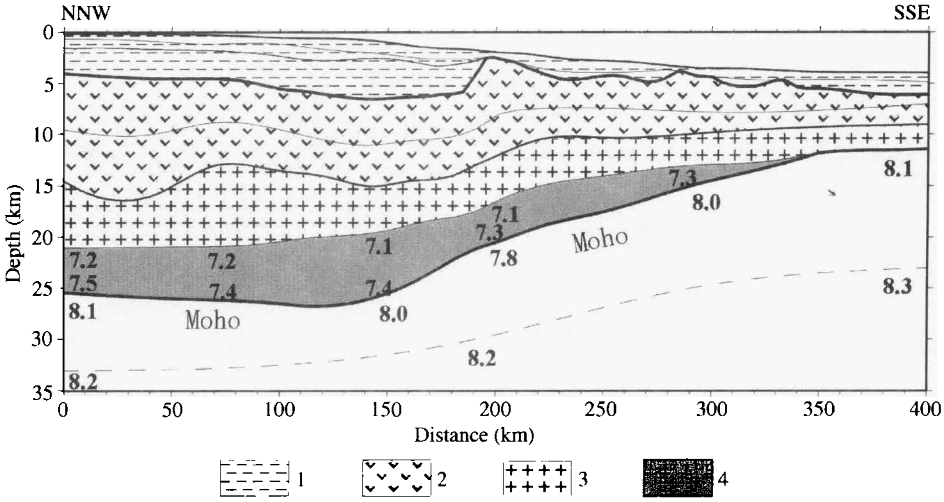

Fig. 4. Crustal structure along the central PRMB profile. Modified from Ref. [4], numbers in the figure indicate P-wave velocity (km/s). 1, Sedimentary layer; 2, upper crust ($V_p < 6.4$ km/s); 3, normal lower crust (6.4 km/s$< V_p <$7.0 km/s); 4, lower crustal HVL ($V_p > 7.0$ km/s).

3.3 Northeastern SCS

In 1995, TOU cooperated with Texas University of USA and completed an east-west OBS profile in the northeastern SCS (Fig. 1). This profile (OBS95) crosses the Hengchun Peninsula of south-most Taiwan and extends from the northeastern SCS to the Philippine Sea. Research results[2] show that the Moho depth is 18 km near the west end of the profile and increases gradually eastward. It is more than 30 km underneath the Hengchun Peninsula. The thickness of the sedimentary layer and the accretionary wedge, as well as the buried depth of the basement interface, also increase in a similar way. The crustal thickness is about 10 km steadily and the upper crust and the lower crust have similar thickness. There is no clear HVL in the lower crust. East of the Hengchun Peninsula, the available crustal structure model[24] shows that the depth to Moho is 12 km near the east end of the profile and increases gradually westward. The Moho depth reaches 17 km, which is still rather small compared to the results of western profile. This may suggest that the Moho interfaces from two different plates be probably overlapped because of the subduction and collision in Taiwan areas.

In August 2001, SCSIO of CAS, TOU and Guangdong Seismological Bureau worked together and completed another OBS profile offshore Shantou City in the northeastern SCS (Fig. 1). This profile (OBS2001), orientated in NNW-SSE, was as long as 500 km. At the same time, land stations using portable seismometers were set up in Nanao Island and Xintang Town along the northern segment of the profile, which is very useful for the deep structure studies of the transition zone of onshore and offshore. The data processing and modeling are well under way[25]1).

4 Comparisons and discussions

The deep seismic experiments and crustal structure studies in the northern SCS have experienced three stages of sonobuoy, two-ship ESP, and OBH/OBS, each having played a positive but different role. The sonobuoy experiments probed mainly the upper crustal structure. The two-ship ESP experiments obtained for the first time the Moho information but their models along the main profiles were rather coarse. And the OBH/OBS experiments obtained more details about the crustal structure. BIRPS once carried out ESP and OBH experiments simultaneously in the central North Sea of UK. The study method of Singh et al.[26] is that the 1-D velocity structure obtained from ESP data was used as the initial model for the OBH data to obtain a 2-D velocity structure. The history of deep seismic experiments in the northern SCS is comparable with that in the world. The

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1) Wang, T. et al. The crustal velocity structure of South China Sea inferred from the OBS experiment and cooperation by both sides of the Taiwan Strait. Abstract for the Fifth Conference on Marine Sciences of Taiwan Nearby Sea Areas, May 2002, Taipei, Taiwan, China (in Chinese).

sonobuoy was popular in the 1970s[27,28]. The ESP was used mainly in the 1980s[29,30]. And from the 1990s, the OBH/OBS proliferated in the international geo-marine sciences[31,32], and has gradually replaced the sonobuoy and ESP since then.

By comparing the research results of nearby ESP and OBH/OBS profiles in the northern SCS, it is discovered that the results of both methods have many coincidences. For example, the buried depths and the shapes of the Moho and basement interfaces are comparable. The overall thickness of the sedimentary layer and the crust are also matched. However, the upper crust is relatively thin and the lower crust is thicker in the ESP models. A HVL with thickness up to 17 km was found in the lower crust beneath the eastern PRMB. On the other hand, the upper crust and the lower crust have similar thickness in the OBH/OBS models, usually no HVLs exist in the lower crust. Only a thin HVL (3～5 km) is seen in the central part of PRMB. In general, the comparison shows that the velocities in the ESP models are overestimated. This is probably because the 1-D structure model of horizontal layers along the tectonic strike was assumed during the data processing and modeling. The crustal structure is quite complex in the northern SCS. The velocity interfaces dip considerably even along the tectonic strike. The presence of dipping layers may be the reasons for the overestimate of the actual velocities.

The results of OBH/OBS experiments in the northern SCS show that there are no or only thin lower crustal HVLs. These results provide supporting evidence for the hypothesis that the northern margin of the SCS belongs to non-volcanic passive continental margins from late Cretaceous[11]. This hypothesis is very favorable for the resource assessment of oil-gas basin in this area. Wu et al.[33] and Yan et al.[34], among others, investigated the magmatic and volcanic activities along the coastal areas of South China and the sea floor spreading history of the SCS. Then they pointed out that the magmatic activities were relatively low during the spreading period of the SCS. The lower crustal HVLs in the eastern PRMB, if they did exist, were not related to the rift spreading and were probably not the result of crustal underplating during the rifting period.

The northern margin of the SCS as a whole is a passive continental margin. But each segment has different characteristics. In the western segment, YGHB is a rift basin formed by the strike-slip pull-apart of Red River Fault. The OBH method did not reach the deeply depressed basin basement. The Xisha Trough is a failed rift, where the crystal crustal thickness is only 8 km in the center of the trough. The crustal structure is distributed symmetrically on both sides of the trough. The middle segment of the northern margin has a broad continental shelf. Its crustal structure thins gradually from continental to oceanic. And this segment experienced the continental rifting and sea floor spreading. The eastern segment of the northern margin was affected significantly by the Taiwan collision zone. Accretional wedge and overlapped Moho are seen underneath the Hengchun Peninsula.

5 Problems and suggestions

The deep crustal structure along the northern margin of the SCS is the most extensively studied among the Chinese continental shelves. Especially the OBH/OBS experiments in the past decade have brought many important results. However, more effort has to be made to catch up with the best studied shelf areas of western countries[35,36]. There are still large areas in the northern SCS, for example, the BBWB, the central and western parts of QDNB and the Baiyun Depression of southwestern PRMB, where many geological problems are poorly understood and thorough investigations are required. The instrument development of OBH/OBS in China is still in the laboratory stage[37]. There are no OBH/OBSs for offshore crustal seismic studies in Mainland China, while Taiwan Ocean University has only 6 OBSs imported from USA. This situation not only limits the OBH/OBS experiments in the northern SCS, but also blocks the deep crustal studies in other offshore areas of China.

In the past, most of the deep seismic surveys onshore and offshore were separated. Thus a blank gap of deep seismic experiments was left in the coastal areas and the onshore-offshore transition zones of the northern SCS. The Binhai Fault of South China is just located in this blank gap so that its deep structure is poorly known. The recent onshore-offshore seismic profile (OBS2001) in the northeastern SCS is a very good attempt.

Because of the limited source energy generated by airgun array, the OBH/OBS method usually can only provide the deep structure information near and above the Moho depth. It is difficult to gain the information from sub-Moho down to the upper most mantle. The earthquake studies can provide velocity information of deeper mantle. The Geophysical Institute of CAS has started the development of Broadband Ocean Bottom Seismometer (BOBS) for the earthquake observation in the offshore areas[37]. We also set up a mobile seismic station on the Yongxin Island of the Xisha Islands[38] (Fig. 1, Xisha station). Such work is worth explorations to acquire earthquake data in the sea and island areas. Furthermore, the measurement of sea bottom heat flow and related studies[3,6] can obtain the information of the lithospheric thermal and rheological structure, which is important for further geo-dynamic studies.

According to the above existing problems, we would like to suggest some important issues of research work in the near future:

(i) Introducing some field proved OBS systems from western countries to speed up the instrument development of OBH/OBSs in China.

(ii) Carrying out the OBH/OBS surveys in oil and gas prospective areas like YGHB, QDNB, and the southwestern PRMB.

(iii) Performing more onshore-offshore deep seismic experiments in order to study the deep structure of the transition zone.

(iv) Setting up more earthquake observations on the islands and sea bottom, and carrying out sea bottom heat flow measurements and the lithospheric thermal and rhelological structure studies to obtain the information from deeper upper mantle.

(v) Extending the OBH/OBS surveys and deep crustal studies in other parts of SCS, including the abysmal basin and the southern margin, comparing their structural characteristics and investigating their relations in order to better understand the evolutionary history of the SCS.

Acknowledgements We would like to thank Academician Jin Qinghuan and Dr. Sanyu Ye for their reviews and helpful suggestions. We are also grateful to Profs. Zhang Yixiang, Huang Ciliu, Chen Xue, Su Daquan and Chen Hanzong for their support during the research work.

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