Distribution and identification of the low-velocity layer in the northern South China Sea*

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Abstract The low-velocity layer (LVL), closely related with tectonic activities and dynamic settings, has always been a hot topic in the deep crustal structure studies. The deep seismic (OBS/OBH) and onshore-offshore experiments have been extensively implemented in the northern South China Sea (SCS) since the 1990s. Six seismic profiles were finished on the northern margin of SCS by domestic and international cooperations. The features of crustal structures were revealed and five velocity-inversion layers were discovered. Among them three LVLs with 3.0—3.5 $km \cdot s^{-1}$ velocity are located in the sedimentary structure (2.0—6.0 km in depth and 2.0—4.6 km in thickness) of the Yinggehai Basin and Pearl River Mouth Basin. They were identified by the reflective and refractive phases for their shallow depth. The other two LVLs with 5.5—6.0 $km \cdot s^{-1}$ velocity generally existed in the middle crust (7.0—18.0 km in depth) with an about 2.5—6.0 km thickness in the transitional crustal structure of the northeastern and northwestern SCS. They were detected by the refractive phase from their overlain and underlying layers. We explored the possible tectonic formation mechanisms combining with previously reported results, which provided evidence for the formation and evolution of SCS.

Keywords: low-velocity layer, deep crustal structure, the northern South China Sea, OBS/OBH and onshore-offshore seismic experiments.

The low-velocity layer (LVL) is generated by different forming mechanisms in the different tectonic units such as platform, rift zone, continental active margin, fold zone, subduction plate, etc.[1—3], and it is closely related with rock melt, magma movements, terrestrial heat actions, hotspring distribution, and strong earthquakes[4]. A hypothesis of continental layer-controlled structures[5] emphasized the importance of the mid-crust ductile layer. Xu[6] considered the LVL, located in the crust, as a high-conductity and low-velocity ductile slip layer. Tectonic activities in micro-plates are mainly controlled by this layer. The vertical delamination indicated the heterogeneity of the crustal structure. LVLs have been found in most of continental crusts in China, such as Qinghai, Tibet, Sichuan, Yunnan, North China, South China, etc.[7—12], and they have already been studied deeply and profoundly. LVLs located in the sea, however, have been less investigated. The conductivity of sea bottom cannot be easily measured since the seawater is a good conductor, so the identification of the low-velocity and high-conductivity layer in the sea becomes much more difficult. The deep seismic OBS/OBH and onshore-offshore experiments have been extensively implemented in the northern SCS since the 1990s. Six seismic profiles (Fig. 1) were finished on the northern margin of SCS by domestic and international cooperations[13]. The project of OBS-1993 was carried out by South China Sea Institute of Oceanology (SCSIO) and Tokyo University of Japan in the middle segment of the northern margin of SCS, and the project of OBS-1995 was completed by the Taiwan Ocean University (TOU) cooperated with Texas University. In 1996, SCSIO and GEOMAR (the Research Center for Marine Geosciences of Germany) collaborated and completed 3 OBH profiles (OBH2-1996, OBH3-1996, OBH4-1996). SCSIO, TOU and Earthquake Administration of Guangdong Province, worked together and completed the profile of OBS-2001 offshore Shantou City in August 2001. These profiles provided a large amount of high-quality deep seismic data. These deep crustal structures have been imaged by data process-

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ing and modeling[11,14—19]1), and these new data and knowledge have further advanced the studies of crustal structure of rift margin in northern SCS and the subduction zone along the Taiwan Island arc. More importantly, these profiles have provided the most fundamental data for the LVL studies of the northern SCS.

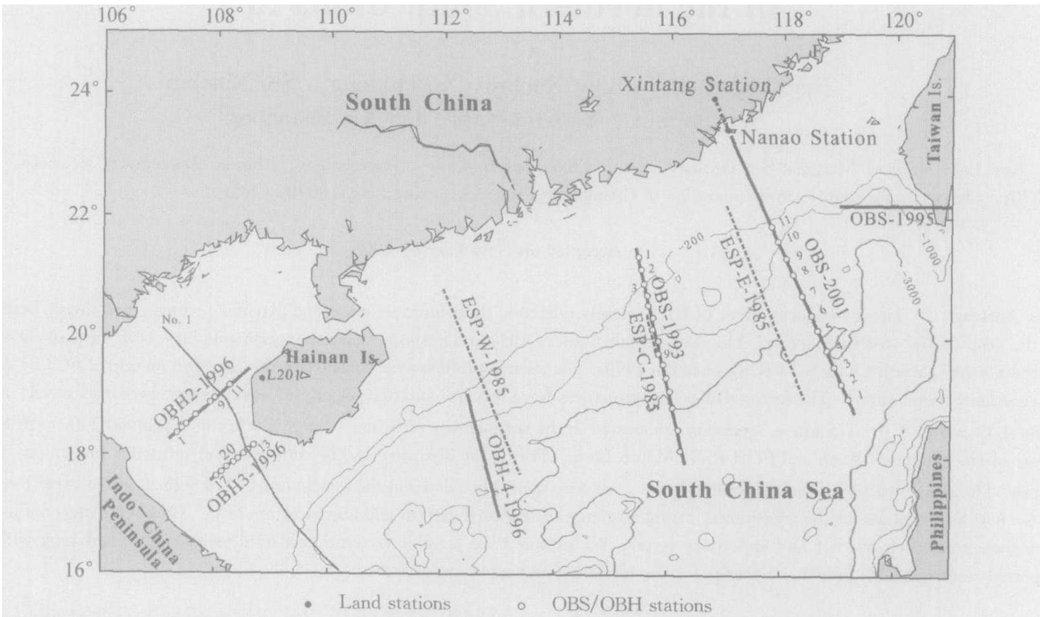

Fig. 1. Location of deep seismic survey lines in the northern SCS. Solid lines indicate OBS/OBH profiles. Dotted lines are extended seismic profiles.

1 LVLs located in the sedimentary layer and their identification

Three LVLs among five LVLs mentioned above are located in the sedimentary layer. Their features are of 2.5—3.0 km·s^{-1} velocity, 2.0—6.0 km depth, and 2.0—4.6 km thickness. They were found in the Yinggehai Basin (YGHB) and the center of Pearl River Mouth Basin (PRMB).

LVLs were discovered in the shallow structure along profiles OBH3-1996 and OBH2-1996 in YGHB. Nine ocean bottom hydrophones (OBH) were set up along OBH3-1996 (Fig. 1). The crustal structure was obtained by ray-tracing and travel time fit (Fig. 2(c))[11]. A LVL at the depth of 3.6 km existed in this structure with about 3.5—4.6 km thickness and 3.0—3.5 km·s^{-1} velocity, whose P-wave velocity decreased 0.7—1.3 km·s^{-1} and 1.0 km·s^{-1} relative to the upper and lower surrounding medium, respectively. The LVL also existed in another structure model of OBH2-1996 (Fig. 5) with about 3.0—5.0 km depth, 2.5 km thickness and 3.0 km·s^{-1} velocity, whose velocity was respectively 0.7—0.9 km·s^{-1} and 1.5 km·s^{-1} smaller than the velocity of its upper and lower layer1). The seismic phases from Moho interface have not been received in the sea area along these two profiles. The lack of seismic signals from deeper basement structure was quite unusual and unexpected. This is very likely caused by the geophysical properties of the underlying structure and unlikely by the energy source or the poor S/N ratio, because the LVL here, acting as a highly energy absorbent, is locally thicker; and the energy of seismic source cannot reach to the Moho interface.

How to identify the above two LVLs located in the sedimentary by the seismic method? The following example of wide-angle seismic data from OBH3-1996 shows the identification method in details. Fig. 2(a) is the seismic record section of OBH20 along OBH3-1996, in which three distinct seismic phase groups, P1, P2P and P3P can be readily identified according to their kinematic and dynamic features. The phase P1 is the first arrival of refraction in sediment and well developed within the offset range of 20 km. But it disappears abruptly beyond this range (Fig. 2). Phase P2P is a near-angle reflection from the top of LVL. P1 and P2P could be seen in all nine OBH-stations. The two endpoints of P1 and P2P are

1) Wu SM, Qiu XL, Zeng GP, et al. Crustal Structure beneath the Yinggehai Basin and adjacent Hainan Island, and its tectonic implication. Deep Sea Research, 2006, accepted.

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converged and tangent to each other at the critical point. If the lower layer is the normal velocity layer rather than LVL, the refractive phase P2, which was from the lower layer and had bigger apparent velocity, should be received out of this critical point. Phases P1, P2 and P3 should be uninterrupted and continuous. But phases P2 and P3 had not been discovered, while P1 disappeared suddenly from all seismic sections of nine OBH-stations. Thus we concluded that the lower layer had the reverse velocity, in other words, it is LVL. It is this LVL that shielded the seismic signal coming back from the deeper crust. It was also inferred from the result of ray tracing and travel time fit in profile OBH3-1996 that the later arrival phase was P3P, rather than P2. P3P was a wide-angle reflection signal and had smaller apparent velocity than refractive phase P2. The ray-tracing path of P3P traveled through the whole LVL, thus its travel time was later and had a similar apparent velocity with P2P. The phase P3P could be traced at four OBH (15, 16, 19 and 20) seismic sections in the central basin. The two-dimensional velocity models were derived iteratively using the ray-tracing method with the help of MacRay program[20]. The crustal structure was well constrained because the observed travel time curves fit very well with the theoretical travel time curves in all nine OBH-stations (Fig. 2 (b), (c)). Therefore, the LVL was identified from the refractive phase of the overlain layer and the reflective phase from the top and bottom of LVL.

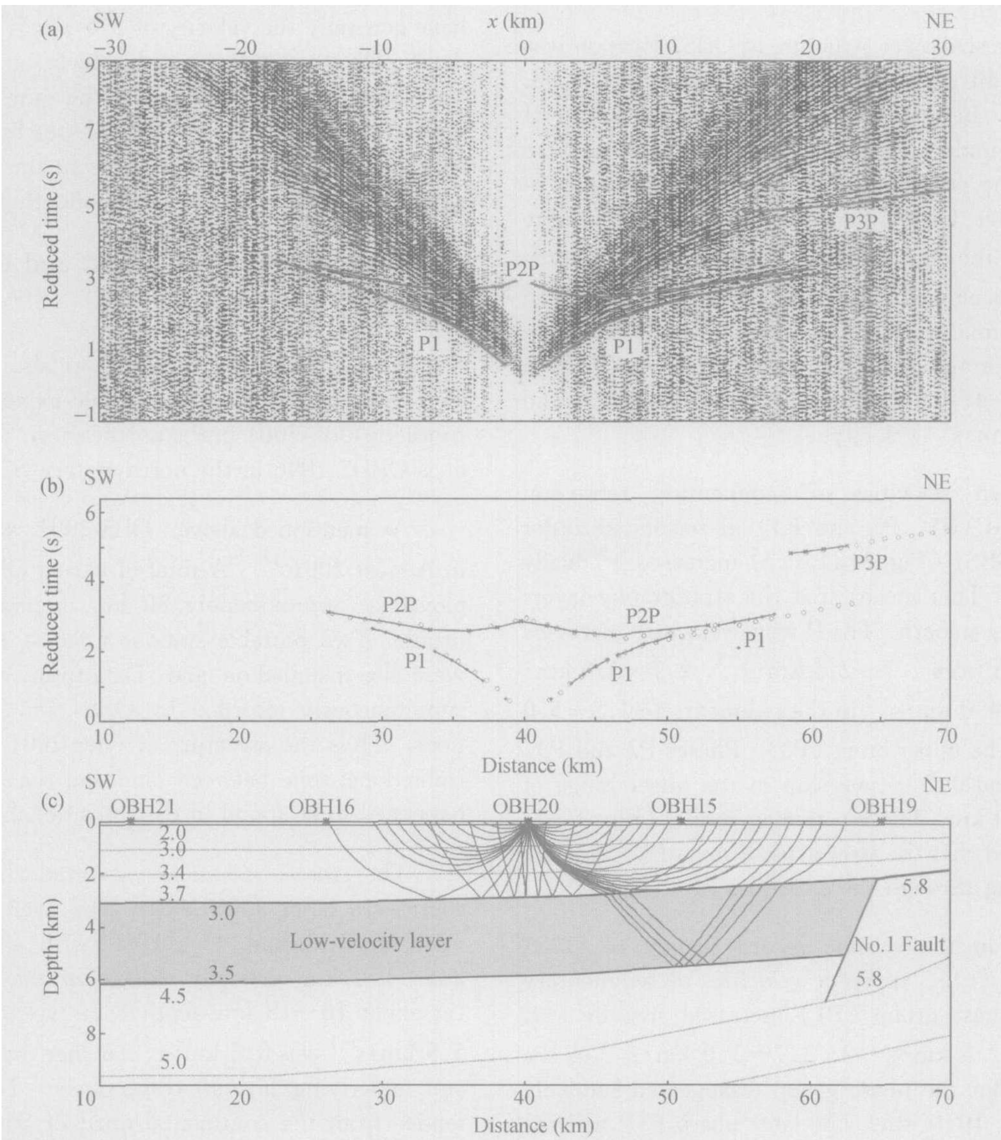

Fig. 2. Ray-tracing and travel time fit in the seismic profile OBH3-1996 at OBH20. (a) Seismic record section, (b) circle symbols stand for observed travel time curves picked up from the record sections (a), while other symbols and their link lines stand for theoretical travel time curves; (c) shows the best fit model and final ray-tracing path of all phases. The seismic data were filtered with a frequency band of 5—15 Hz. Reduced velocity: $v_r = 6.0\ km \cdot s^{-1}$, x stands for the distance between station and shot, reduced time: t_r = travel time − $x/6$.

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The third LVL in sediment existed in the PRMB. A Sino-Japan survey project OBS-1993 was carried out across the PRMB, the central section of the northern margin of SCS. Fifteen Ocean Bottom Seismometers (OBS) were deployed, and both airgun and explosive were used as seismic sources. Clear phases from Moho were received. The two-dimensional kinematic ray tracing was employed to construct and define the crustal structure[15]. The crustal thickness decreased from 22 km in the littoral area to 8 km in the deep sea. The thickness of the sediment and crust over the upper slope were 5 km and 8—10 km, respectively. A high velocity layer with an average thickness of 4 km was found in the base of the lower crust.

But the shallower structure at OBS2 location was difficult to fit well. It was a suspicion that LVL might exist. In order to pinpoint the crustal nature of this area, single channel seismic data were used to construct the original model, and the deep-penetration refractive OBS data (Fig. 3(a), (b)) were reused for the ray-tracing and the MacRay program[20] was employed for travel time fit (Fig. 3(c), (d)). The final model demonstrated that LVL surely existed under the shallower structure of OBS2 with about 2.0—4.0 km depth, 2.0 km thickness and 2.5—3.0 $km \cdot s^{-1}$ velocity.

Apparent velocities of sedimentary refraction phase groups (P1, P2 and P3) in seismic recorder section of OBS1 (Fig.3(a), (c)) increased gradually with depth. That means that the stratigraphy layers are relatively smooth. The P-wave velocities increased inch by inch from 1.7—2.5 $km \cdot s^{-1}$, 2.7—3.0 $km \cdot s^{-1}$, 3.3—4.0 $km \cdot s^{-1}$ in the sediment, to 4.5—5.0 $km \cdot s^{-1}$ in the upper crust (P3). Phases P2 and P3, however, had 0.3 s time-skip in the offset range of 22.0—24.0 km. The ray-tracing results (Fig.3(c), (d)) showed that the later arrival time of P3 was due to its passing through the entire LVL.

While in the seismic record section of OBS2 (Fig.3(b), (c)), apparent velocities of sedimentary refraction phase group (P1) increased step by step from 1.7—2.5 $km \cdot s^{-1}$ to 2.7—3.0 $km \cdot s^{-1}$ in the sediment. But the phase group disappeared suddenly out of offset 10.0 km. The later phase P3P had the time delay of about 1.0 s. The sharp local phase drop appeared in the refraction phases within deposits. This phase drop predicts the possible existence of one of the following factors: major fault, high dipping angle or LVL[15]. In the reflection seismic data, however, the deposits were very flat around OBS2 and no major fault and high dip angle were found from the single channel seismic profile. Thus LVL was introduced into the model to compensate the substantial time delay. After LVL with 2.5—3.0 $km \cdot s^{-1}$ velocity was interposed in the final model, all phases of OBS1 and OBS2 fit very well. P3P was the reflective phase from the bottom of LVL. P1 was defined as the refraction from the overlain layer of LVL. Both of them well constrained the LVL.

Currently LVLs located in sediment were discovered in these three profiles only. Their main features have generally the velocity of 2.5—3.5 $km \cdot s^{-1}$, the depth of 2.0—6.0 km and the thickness of 2.0—4.6 km. They can be identified by the same method and discriminated by the refraction phases from the overlain layer and reflection phases from the top and bottom of LVL due to their shallow depth.

2 LVLs located in the crust and their identifications

LVLs located in the crust were also discovered in two profiles with the deep seismic explorations. One profile is OBS-2001 in the northeastern SCS, the other is OBH2-1996 in the northwestern SCS (Fig.1).

As mentioned above, OBS-2001 was completed in August 2001[13]. A total of eleven OBSs were deployed at approximately 30 km intervals along the profile. Two portable stations (Nanao and Xintang) were also installed on land. Data from each shot were simultaneously recorded by OBSs and portable stations. Thus the structure of OBS-2001 included the transitional zone between land and sea. And a LVL happened to be found in the transitional zone[21].

The crustal thickness was gradually decreasing southward along OBS-2001. The average thickness was about 28 km. One LVL with a thickness of 2.5—4.0 km generally existed in the middle crust (at about 10—18 km depth). Its velocity of 5.5—5.9 $km \cdot s^{-1}$ was 0.5 $km \cdot s^{-1}$ smaller than its overlain and underlying layers, respectively. The LVL extended from the continental crust of South China to the shelf off 150 km southeastern Nanao island, and pinched out nearly beneath Dongsha uplift. We will discuss the identification method of LVL in crust as

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below, taking the ray-tracing and travel time fit of Nanao station as an example.

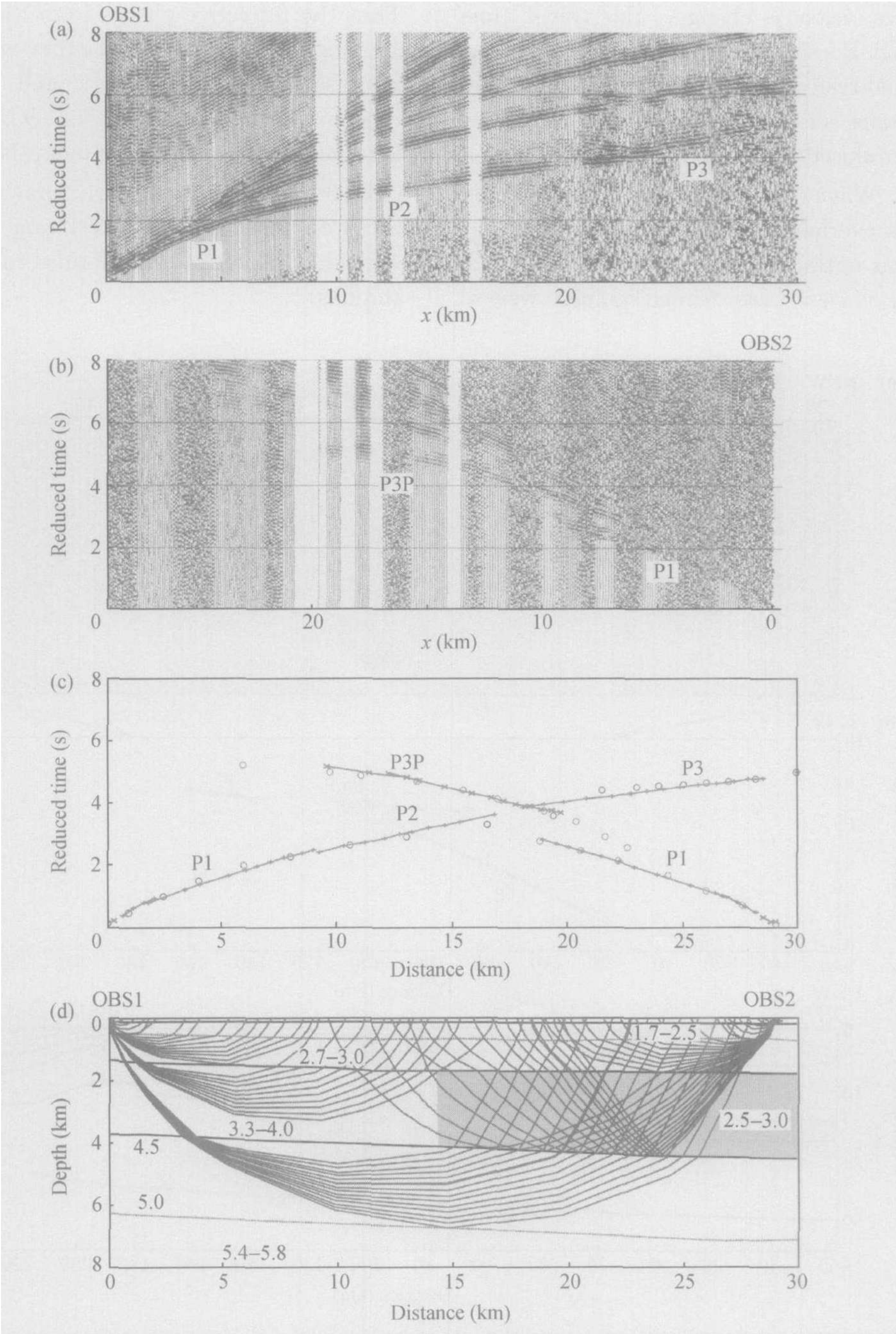

Fig. 3. Final model with ray-tracing and travel time fit along the profile OBS-1993. (a) and (b) are OBS1 and OBS2 seismic record sections, respectively, (c) circle symbols stand for observed travel time curves picked up from record sections(a) and (b), while the other symbols and their link lines stand for theoretical travel time curves; (d) shows the best fit model and final ray-tracing path of all phases. The shadow part is LVL. The seismic data were filtered with a frequency band of 5—15 Hz. Reduced velocity: $v_r = 8.0$ km·s^{-1}, x stands for the distance between station and shot, reduced time: t_r = travel time $- x/8$.

In Fig.4, Pg is the refraction from the Cenozoic basement. Pc is the refraction from the lower crust. Pn and PmP are the head wave and the reflection from the Moho interface, respectively. Pg is the dominant phase in the offset range of 15—110 km. Pg phase can be seen clearly and traced continuously on all the record sections, which indicates that the structure of the basement is not very complicated and

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the velocity changes not so much. The upper crust has a normal velocity distribution. If the lower crust has also positive velocity change, the travel time curves of Pg and Pc should be continuous. But the blank area existed really between Pg and Pc in both of Nanao and Xintang seismic sections (Fig.4). It was the LVL that produced the ray-path shade and travel-time skip[22,23]. Wave impedance of LVL was smaller than both of its overlain and underlying layers. The wave energy was entrapped inside this LVL, which formed channel waves, also named guided waves. That means the reflection signal only occurred inside the LVL as a result of no exhibition of refraction. Thus the refractive phases from the overlain and underlying layers of LVL, in other words, Pg and Pc, are disconnected and interrupted. The two travel-time curves have a skip. This LVL was controlled by four seismic stations of Xintang, Nanao, OBS11 and OBS10[21]. The crust structure was more reliable based on that the real travel time curve fitting well with the theoretical travel time curves of these four stations.

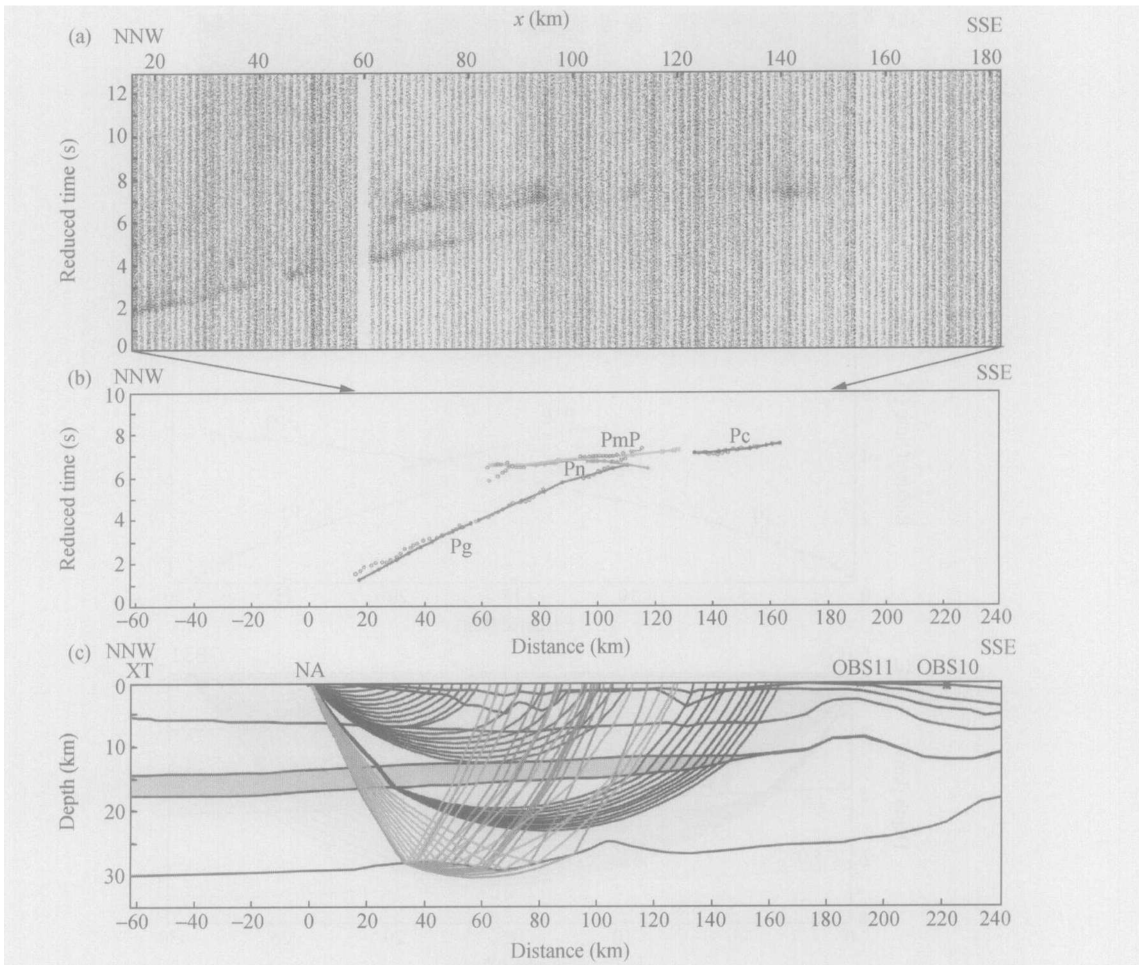

Fig. 4. Ray-tracing and travel time fit of Nanao station along the profile OBS-2001. (a) The seismic record section of Nanao, (b) circle symbols stand for observed travel time curves picked up from record section (a), while the other symbols and their link lines stand for theoretical travel time curves; (c) shows the best fit model and final ray-tracing path of all phases. The shadow part is LVL. The seismic data were filtered with a frequency band of 5—15 Hz. Reduced velocity: $v_r = 8.0\ \mathrm{km \cdot s^{-1}}$, x stands for the distance between station and shot, reduced time: t_r = travel time $- x/8$.

Another profile OBH2-1996 was placed in the northwestern SCS. Due to the interference of severe typhoon and fishing net, only four stations (OBH1, 2, 9 and 11) were retrieved from twelve seismic OBH-records. Owing to existing of the LVL, the seismic sections of four OBHs had not received deep signals from Moho1)[24]. But one land station (L201) was successfully installed along the profile extension.

1) See footnote on page 592.

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The seismic section of L201 showed a good S/N ratio and has a number of clear seismic phases (Pg, Pc, PmP and Pn).

Pg is the refraction from the basement and shows the apparent velocity of 5.7—6.1 $km \cdot s^{-1}$ of the upper crust. Pc is the refraction from the lower crust and indicates the apparent velocity of 6.4—6.7 $km \cdot s^{-1}$. PmP and Pn are the wide-angle reflection and refraction from the Moho, respectively.

Generally structure model has seismic velocity changing continuously with depth. The boundaries of different velocity gradients can be regarded as interfaces of the velocity discontinuities. If both the upper and lower crust have positive velocity gradients, the travel time curves of Pg and Pc should be continuous and only the two curves have different curve slopes, in other words, different apparent velocities[21]. The time skip of 1.2 s, however, existed between Pg and Pc in L201 seismic sections (Fig.5). That means the thicker LVL is responsible for the bigger time skip. The crustal structure of OBH2-1996 was also acquired by using the ray-tracing and travel time calculating with the help of the program MacRay[20] (Fig.5(b), (c)). The LVL existed in the northern of Fault No. 1 of the crustal structure with 5.5—6.0 $km \cdot s^{-1}$ velocity, 7.0—13.0 km depth, 6.0 km thickness. The velocity of LVL was 1.2 $km \cdot s^{-1}$ and 0.4 $km \cdot s^{-1}$ smaller than the overlain and underlying layers, respectively.

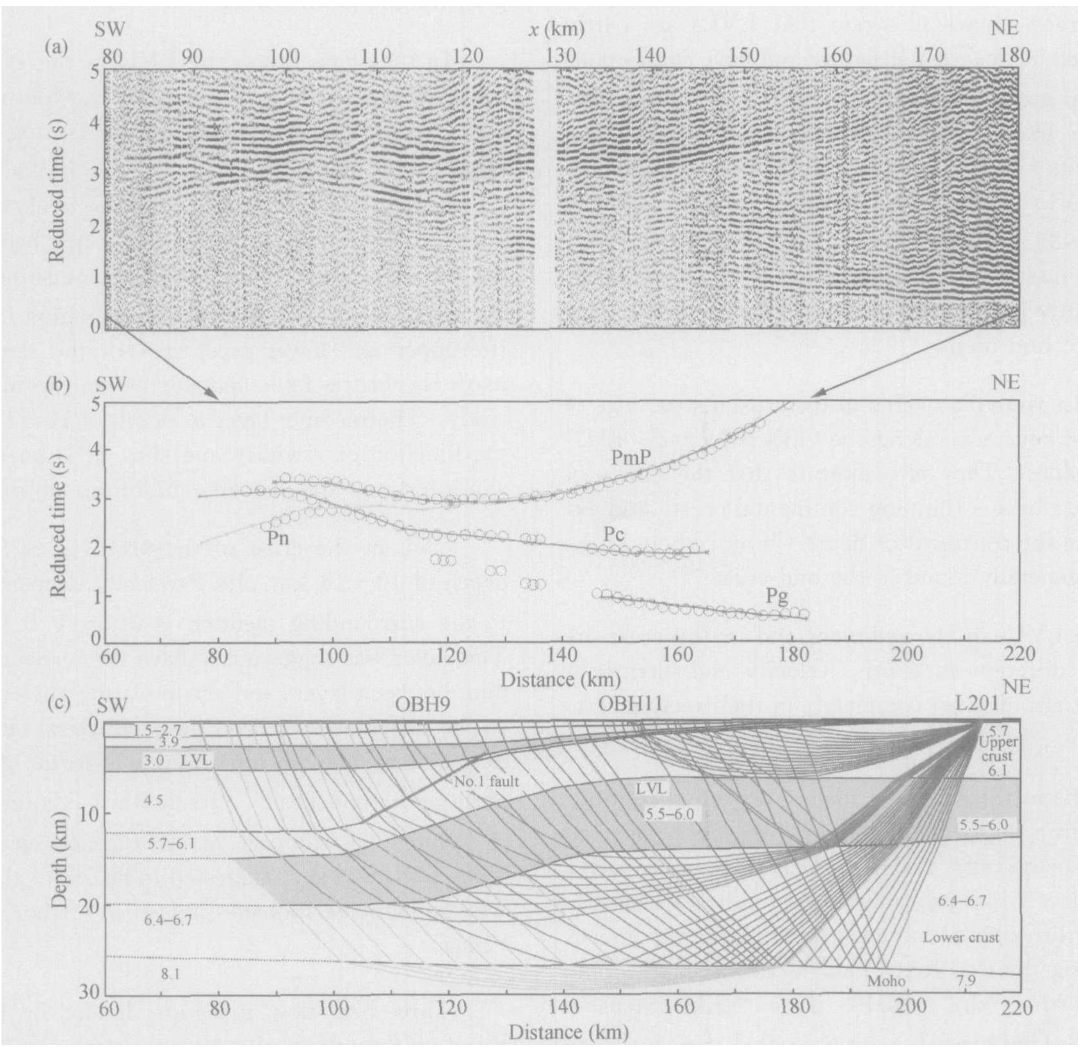

Fig. 5. L201 ray-tracing and travel time fit in the seismic profile OBH2-1996. (a) The seismic record section of L201, (b) circle symbols stand for observed travel time curves picked up from record section (a), while the other symbols and their link lines stand for theoretical travel time curves; (c) shows the best fit model and final ray-tracing path of all phases. The shadow part is LVL. The seismic data were filtered with a frequency band of 5—15 Hz. Reduced velocity: $v_r = 6.0$ $km \cdot s^{-1}$, x stands for the distance between station and shot, reduced time: t_r = travel time $- x/6$.

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The two LVLs in the above OBH2-1996 and OBS-2001 have the similar characteristics. Both of them located in the crust with 5.5—6.0 $km \cdot s^{-1}$ velocity, 7.0—18.0 km depth, 3.0—6.0 km thickness. Thus they have the same identification method based on the travel-time skip of Pg and Pc.

3 Discussion

The deep seismic (OBS/OBH) and onshore-offshore experiment is one of the most effective methods to study the crustal structure and LVL. It has the advantages of both the wide-angle reflection and refraction. It has greatly developed in the northern SCS since the 1990s, and also offered a considerable amount of information on the study of LVL.

Current studies illustrate that LVLs are partly distributed in the crust structure and have connections with local geotectonic activities[1,3,7,8,25]. These layers more likely reflect low-angle fault zones, and movements along which cause tectonic layering of the crust. LVLs were not found in other profiles, such as ESP-E-1985, ESP-C-1985 and ESP-W-1985[26], probably due to the fact that either LVLs were developed rightly in that area or the precision was not good enough to find them.

LVLs were discovered in the crustal structures of the transitional zone along the OBS-2001 and OBH2-1996 profiles. They also indicate that the crusts of these areas have a thinning continental crust, and extend from the continent of South China, where LVLs are also generally found in the mid-crust[25,27,28].

The LVLs in the sediment and in the crust are not only different in depth, velocity and identification, but also distinct completely in their tectonic formation.

LVLs in the sediment mainly deposited continuously with a high rate and formed by less-compacted strata. Tectonically YGHB had endured multi-period rift events. It was probably generated by two mechanisms of lithosphere extension and strike-slip movement along the Red River Fault Zone. It is generally assumed that the YGHB is a strike-extension basin[29]. This basin has been studied very well due to its special tectonic location and rich hydrocarbon. Abundant dataset from many multi-channel reflection profiles, wide-angle reflection/refraction profiles, oil wells and stratum pressure have testified that the LVLs in the sediment are found in the YGHB. The main cause of LVL formation is that the sediment deposits rapidly[29,30]. The sedimentary rate varies from 0.5 to 1.4 mm/yr since the mid-Eocene[31]. The well log shows a dramatic drop of velocity, from normally 3.2 $km \cdot s^{-1}$ even down to 2.5 $km \cdot s^{-1}$, and normally an increase of porosity from 13%—18% to 13%—40%[29]. It is also a high-pressured zone in YGHB, which is explained as a result of under-dewatering due to rapid subsidence based on the geological and geophysical features of the basin. In another region, the LVL is more likely related with the porous layer or fractured zone rich of hydrocarbons in the central part of Pearl River Basin. Thus the P velocity of the layer decreases as a result of the increase of porosity and permeability[15].

In the same time, the LVL in the crust has a close relation with rock partly melt, volcano activities, terrestrial heat movement, hotspring distribution, and strong earthquakes[4]. The LVLs located in the medium crust are tectonically the weakened crusal layer, representing the ductile-shear belt between layers and reflecting the brittle-ductile transitional deformation of rocks[32]. The rock deformation features in the upper and lower crust are not the same. They mark the brittle fault and ductile transform, respectively. The medium layer at depth of 10—18 km has the function of viscidity and slip. It is an important slip interface, and also an equilibrium-adjust layer.

LVL in the crust of the northern SCS has the depth of 10—18 km. Its P-velocity decrease relative to the surrounding medium is 0.5—1.0 $km \cdot s^{-1}$. This layer was suggested to have the tendency of slipping between layers and accumulating the energy due to the differences of layering geophysical characteristics. It may play an important role in the generation of large earthquakes[33]. Its depth is relative to depth of layered distribution of earthquake epicenter[9]. Thus LVL was also suggested to be one of the reasons why so many earthquakes happened offshore of South China.

Three heat flow zones are divided by Kuszir[34] based on the relationship between temperature, depth and heat flow values. In the middle heat flow zone (the value is 60—70 $mW \cdot m^{-2}$), the weakened belt maybe occurred in the depth of 35 km corresponding to Moho interface and the depth of 18 km correspond-

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ing to LVL[34]. The heat-flow values of the northeastern and northwestern parts of SCS are 65 $mW \cdot m^{-2}$ and 79 $mW \cdot m^{-2}$, respectively[35]. These areas belong to the middle heat flow zone. Thus the LVL maybe formed in the crustal structure under this heat flow condition.

However, LVL is generally related with tectonic activities and dynamic settings[1,3,25]. Its detailed formation mechanism must be studied further when much more data are obtained, which is important for the formation and evolution theory of SCS.

4 Conclusions

(1) The five LVLs were discovered in northern SCS, and three LVLs with 2.5—3.0 $km \cdot s^{-1}$ velocity, 2.0—6.0 km depth, 2.0—4.6 km thickness were located in the sedimentary layer. They were respectively found in YGHB and PRMB. The other two LVLs (5.5—6.0 $km \cdot s^{-1}$ velocity) existed generally on the bottom of the upper crust (7.0—18.0 km depth) with about 2.5—6.0 km thickness in the transitional crustal structure of the northeastern and northwestern SCS.

(2) LVLs in the different depths have different identification methods. The LVLs located in sedimentary structure usually have shallower depth and the reflective phase from the base of LVL can be received. They can be identified by the reflective and refractive phases. The LVLs existed in the crust can be detected from two refracted phases from their overlain and underlying layers because the LVLs have a deeper depth and the reflective phase cannot be received. These two refracted phases have a time-skip feature.

(3) LVLs in different depth have different formation mechanisms. Based on the geological and geophysical features of the basin, LVLs in the YGHB were probably generated and formed by less-compacted strata when depositional rate was very high, while the LVL occurred in the center of PRMB might be related with the porous layer or fractured zone rich in hydrocarbon.

The LVLs located in the middle crust are the weakened medium layer, representing the ductile-shear belt between layers and reflecting the brittle-ductile transitional deformation of rocks. Its depth is relative to the depth of earthquake epicenter. Thus LVL is also suggested to be one of the reasons why so many earthquakes happened offshore of South China.

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References

1 Zorin YA, Mordvinova VV, Turutanov EK, et al. Low seismic velocity layers in the Earth's crust beneath Eastern Siberia (Russia) and Central Mongolia: receive function data and their possible geological implication. Tectonophysics, 2002, 359: 307—327

2 Lin CH, Huang BS and Rau R. Seismological evidence for a low-velocity layer within the subducted slab of southern Taiwan. Earth and Planetary Science Letters, 1999, 174: 231—240

3 Schmitz M, Heinsohn WD and Schiling FR. Seismic, gravity and petrological evidence for partial melt beneath the thickened Central Andean crust (21°—23°S). Tectonophysics, 1997, 270: 313—326

4 Yang XS, Ma J and Zhang XJ. summarization of genesis of Low-velocity layer in continental crust. Geological Science and Technology Information (in Chinese), 2003, 22(1): 35—41

5 Li YQ, Zhang XL and Chen YC. A hypothesis of continental layer-controlled structures: a new genetic model for evolution of basin-range systems and orogenic belts. Geology of Chemical Minerals (in Chinese), 1996, 18(3): 149—155

6 Xu KD. Analysis on lithosphere structure of South China. Marine Origin Petroleum Geology (in Chinese), 2000, 2(2): 31—46

7 Wang ZL, He QD and Meng LS. The crustal structure of the northern margin of Qinghai-Tibet plateau and its genetic analysis. World Geology (in Chinese), 2002, 21(2): 105—116

8 Xiong SB and Liu HB. Crust-mantle structure of Zhejiang-Anhui region and the boundary between Yangzi Block and Huanan Block. Progress in Geophysics (in Chinese), 2000, 15(4): 3—17

9 Zhou YS and He CR. The relationship between low velocity layers and rheology of the crust in north China and its effect on strong earthquake. Seismology and Geology (in Chinese), 2002, 24(1): 124—132

10 Zhang Z, Jose B, Li Y, et al. Crust-upper mantle seismic velocity structure across southeastern China. Tectonophysics, 2005, 395: 137—157

11 Xia KY, Zhou D, Su DQ, et al. The velocity structure of the Yinggehai basin and its hydrocarbon implication. Chinese Science Bulletin, 1998, 43(24): 2047—2055

12 Liu GD, Shi SL and Wang BJ. The relationship between the high conductivity layer and crustal tectonic activities in North China. Science in China (Ser. B) (in Chinese), 1984, 9: 839—848

13 Qiu XL, Shi XB, Yan P, et al. Recent progress of deep seismic experiments and studies of crustal structure in northern South China Sea. Progress in Natural Science, 2003, 13(7): 481—488

14 Qiu XL, Ye SY, Wu SM, et al. Crustal structure across the Xisha Trough, northwestern South China Sea. Tectonophysics, 2001, 341: 179—193

15 Yan P, Zhou D and Liu ZS. A crustal structure profile across the northern continental margin of the South China Sea. Tectonophysics, 2001, 338: 1—21

16 Chen AT and Nakamura Y. Velocity structure beneath eastern offshore of southern Taiwan based on OBS data and its tectonic significance. TAO, 1998, 9(3): 409—424

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17 Nakamura Y, McIntosh K and Chen AT. Preliminary results of a large offset seismic survey west of Hengchun Peninsula, southern Taiwan. TAO, 1998, 9(3): 395—408

18 Zhao MH, Qiu XL, Ye CM, et al. Analysis on deep crustal structure along the onshore-offshore seismic profile across the Binhai (littoral) fault zone in NE south China Sea. Chinese J. Geophys. (in Chinese), 2004, 47(5): 845—852

19 Wang TK, Chen MK, Lee CS, et al. Seismic imaging of the transitional crust across the northeastern margin of the South China Sea. Tectonophysics, 2006, 412: 237—254

20 Luegert JH. MacRay: Interactive Two-Dimensional Seismic Raytracing for the Macintosh™. U. S. Open File Report 92—356. Menlo Park, California, Department of the Interior U. S. Geological Survey, 1992, 1—44

21 Zhao MH, Qiu XL, Xu HL, et al. Crustal structure and its low-velocity layer in the transitional zone of South China. Journal of Tropical Oceanography (in Chinese), 2006, 25(5): 36—42

22 Zeng RS. Solid Earth Geophysics (in Chinese). Beijing: Science Press, 1984, 54—57

23 Aki K and Richards PG. Quantitative Seismology Theory and Methods. W H Freeman and Company, 1930, 404—411

24 South China Sea Institute of Oceanology, Chinese Academy of Sciences. The Crustal Structure from the Wide-Angle Seismic Data, in the Northwestern South China Sea (in Chinese). Resource and Environment Project of Chinese Academy of Sciences (KZ952-S1-416), 2000, 8—14

25 Zhu JF, Xu XW, Zhang XK, et al. Joint exploration of crustal structure in Fuzhou basin and its vicinities by deep seismic reflection and high-resolution refraction as well as wide—angle reflection/refraction. Science in China (Ser. D), 2005, 48(7): 925—938

26 Yao BC, Zeng WJ, Hayes DE, et al. The Geological Memoir of South China Sea Survey Jointly by China and USA (in Chinese). Beijing: China University of Geosciences Press, 1994, 1—203

27 Liao QL, Wang ZM, Wang PL, et al. Explosive seismic study of the crustal structure in Fuzhou-Quanzhou-Shantou region. Chinese J. Geophy. (in Chinese), 1988, 31(3): 270—280

28 Yin ZX, Lai MH, Xiong SB, et al. Crustal structure and velocity distribution based on deep seismic sounding along the Lianxian-Boluo-Gangkou profile in southern China. Chinese J. Geophys. (in Chinese), 1999, 42(3): 383—392

29 Wu SM, Zhou D, Qiu XL, et al. Characteristic and genesis of low velocity layer in Yinggehai basin, NW south China Sea. Journal of Tropical Oceanography (in Chinese), 2001, 20(3): 8—14

30 Zhu FB and Tian SC. Mudstone compaction and primary migration of oil gas in Yinggehai basin. China Offshore Oil and Gas (Geology) (in Chinese), 1998, 12(5): 306—311

31 Gong ZS, Li ST, Xia KY, et al. Continental Margin Basin Analysis and Hydrocarbon Accumulation of the Northern South China Sea (in Chinese). Beijing: Science Press, 1997, 510

32 Jiang BH, Yuan DW and Wu YH. Relation of low-velocity crustal layers with earthquake activities. Geological Science and Technology Information (in Chinese), 1992, 11(4): 9—15

33 Xu HL, Qiu XL, Zhao MH, et al. Characteristics of the crustal structure and hypocentral tectonics in the epicentral area of Nan'ao Earthquake (M7.5), the northeastern South China Sea. Chinese Science Bulletin, 2006, 51: 83—91

34 Kuszir NJ and Park RG. The extentional strength of the continental lithosphere, its dependence on geothermal gradient and crust composition and thickness. Continental Extensional Tectonics, 1987, 28: 35—53

35 Shi XB, Qiu XL, Xia KY, et al. Heat flow characteristics and its tectonic significance of South China Sea. Journal of Tropical Oceanography (in Chinese), 2003, 22(2): 63—73

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