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Review

Study and review on crust-mantle velocity structure in Bohai Bay and its vicinity*

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Abstract

Observational data from some of the 10-odd deep seismic sounding profiles in Bohai Bay and its adjacent areas were processed with the methods of two-dimensional ray tracing, travel-time fitting and synthetic seismogram. The crust and upper-mantle velocity structure model in this area was built. The results show that the crust and upper mantle structures present obvious lateral and vertical inhomogeneity. The upper mantle uplifts near Yongqing of northeast Jizhong depression, in Bohai Bay of Huanghua depression and near Kenli of Jiyang depression, where crustal depths are about 31 km, 28 km and 29 km, respectively. According to the dynamic and kinetic characteristics of seismic waves as well as the seismic interfaces and velocity contour undulation in the 2-D velocity structure model, three deep crustal fault zones are inferred in the area. Low velocity (5.90~6.10 km/s) layers (bodies) exist on one or two sides of these deep crustal fault zones.

Key words: deep seismic sounding; crust and upper mantle; velocity structure; seismic interfaces
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Introduction

Bohai Bay, along with its adjacent areas, is one of the seismically active areas in North China. Understanding its crust/upper-mantle structural characteristics and lateral heterogeneity of the medium in this area is of great significance to the study of seismogenic environment, thus improvimg the level of earthquake prediction. For years, scientists have studied the area by gravity and magnetic methods (FENG, *et al*, 1989), geothermal field (WU, *et al*, 1988; TIAN, ZHANG, 1992), magnetotelluric sounding (LIU, *et al*, 1984) and deep seismic sounding (SUN, *et al*, 1988; ZHANG, *et al*, 1994, 1998; LI, *et al*, 2001), and have yielded significant results.

The correlation between crust/upper-mantle velocity structures and seismicity in Bohai Bay and its adjacent areas has been studied by DSS wide-angle reflection/refraction techniques. After the Tangshan earthquake, *i.e.* from 1976 to 1993, the Research Center of Exploration Geophysics (RCEG) under CSB completed a great number of DSS wide-angle reflection/refraction profiles

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(Figure 1), with the purpose of studying crust upper-mantle velocity structures, deep seismogenic environment and providing deep crustal information for exploiting deep mineral resources in the area. In this paper, data from 3 (*H*-02, *H*-04 and *H*-10) of the 14 DSS profiles displayed in Figure 1 are interpreted for 2-D crust and upper-mantle velocity structure on the basis of previous 1-D interpretation. The depth contour maps of interfaces C_1, C_2 and M-discontinuity have been made in the light of the previous results from other scientists. Some 2-D results from the L_2 and L_4 profiles that have not been published are used in the determination of the crustal interfaces and M-discontinuity.

1 Profile layout and tectonic setting

Figure 1 shows the locations of the 14 DSS profiles in the studied area. More than 80 explosions (with 1 000 kg-charge) were conducted along these profiles totaling 3 200 km in length. Two of the explosions were carried out offshore on the Dezhou-Qinhuangdao profile (VIII), which passes through the water area of the Bohai Bay. In plain areas, the average shot point gap is small, *i.e.* 30~40 km and receiver spacing 2~3 km; in mountainous areas, the average shot point gap is

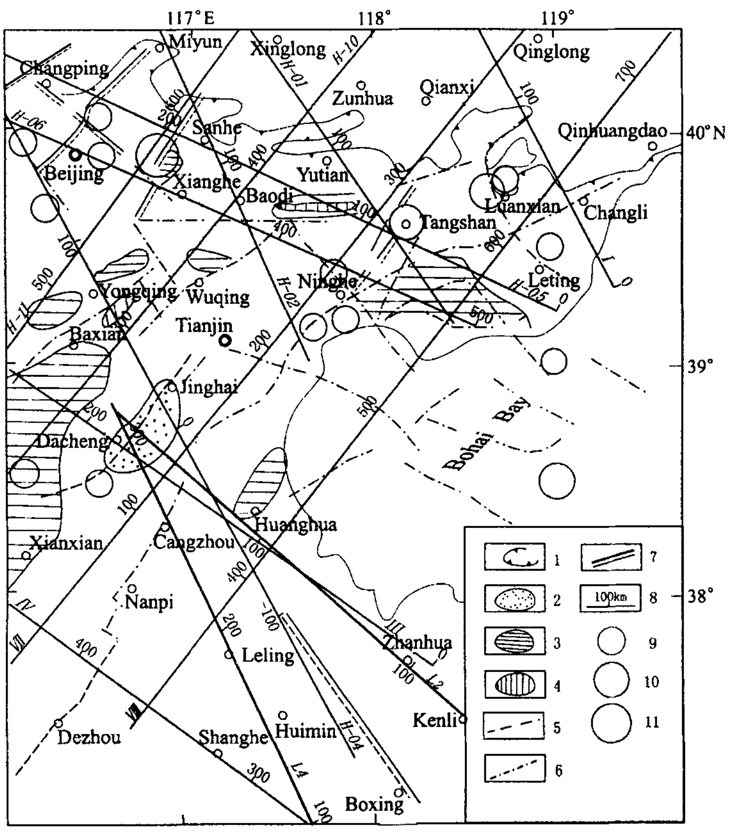

Figure 1 DSS profiles and seismic structure of Bohai Bay and its adjacent areas (from XU, *et al*, 1998)
1. Basin boundary; 2. 300 m-thick Quaternary system; 3. 400~700 m-thick Quaternary system; 4. 700~1 000 m-thick Quaternary system; 5. Actual and inferred faults; 6. Hidden faults; 7. Active faults since the late Pleis tocene Epoch; 8. DSS profiles; 9. M=6.0~6.9; 10. M=7.0~7.9; 11. M=8. I. Changli-Chengde profile; III. Haixing-Yangyuan profile; IV. Zhucheng-Dingxian profile; VII. Cangzhou-Kazuo profile; VIII. Dezhou-Qinhuangdao profile; *H*-01. Baigezhuang-Zhenglanqi profile; *H*-02. Tanggu-Miyun profile; *H*-04. Yanshan-Yanqing profile; *H*-05. Leting-Zhangjiakou profile; *H*-06. Ninghe-Zhuolu profile; *H*-10. Anguo-Zunhua profile; *H*-11. Shijiazhuang-Kalaqinqi profile; L_2. Shouguang-Wen'an profile; L_4. Yiyuan-Dacheng profile

relatively large, *i.e.* 60~80 km and receiver spacing 3~4 km. These DSS profiles form an observational network in the studied area, making it an area with the densest DSS profiles, the most complete observational system and the most plentiful data on the crust and upper mantle.

The DSS profiles pass through the areas such as Beijing, Tangshan, Tianjin, Bohai Bay, Cangzhou and Huimin. In terms of tectonic setting, the studied area involves the middle/southern sections of the nearly EW-oriented Yanshan uplifted area and the middle section of the Cenozoic rift system of the North China plain east of the Taihangshan lifted area. The rift system, in NNE direction on the whole, contains a series of uplifts and depressions, and the depressions in turn contain a great number of swells and sags, presenting a fragmented appearance. Surrounding the rift system are mostly large boundary faults, within which a number of NNE-NE and some NWW-NW secondary faults develop. Almost all the faults are tensional, whose dip angles become lower with the increase of depth. Most of the faults came into being during the badly downfaulting of the Eogene Period, and some larger faults were still active in the Neogene Period. A large number of tensional faults are found in Bohai Bay area in the sedimentary layers of the Neogene Peroid and even of the Quaternary Period, which indicates continuous faulting in this area (XU, *et al*, 1998).

According to historical records and modern instrumental records, 17 $M \geq 6.0$ earthquakes and a great number of moderate and small earthquakes have taken place in Bohai Bay and its neighborhood. Among them, one is an M=8.0 event, 3 M=7.0~7.9 events and 13 M=6.0~6.9 events. Figure 1 shows that most of the earthquakes took place to the north of Bohai Bay, in Luanxian, Tangshan, Ninghe, Sanhe and Beijing, which jointly form one of the most seismically active areas in North China.

2 Basic crust-mantle velocity structures and tectonics

2-D interpretation of the data from more than 10 DSS profiles in Bohai Bay and its adjacent areas displays obvious vertical and lateral heterogeneity of crust and upper mantle structures. The crust is of layered structure, with interface C_2 as the rough boundary surface between the upper crust and the lower crust. It separates the brittle upper crust from the relatively ductile lower crust and plays the role of transferring deformation and decoupling between the upper and lower crust (ZHANG, *et al*, 1996). The upper crust ranges from the surface layer to interface C_2; the lower crust ranges from C_2 to Moho. Different interface depths determined from the DSS profiles were used to make the depth contour maps of C_1, C_2 and Moho (Figures 2, 3 and 4). Figure 5 shows 2-D velocity structure and tectonics of the crust and topmost

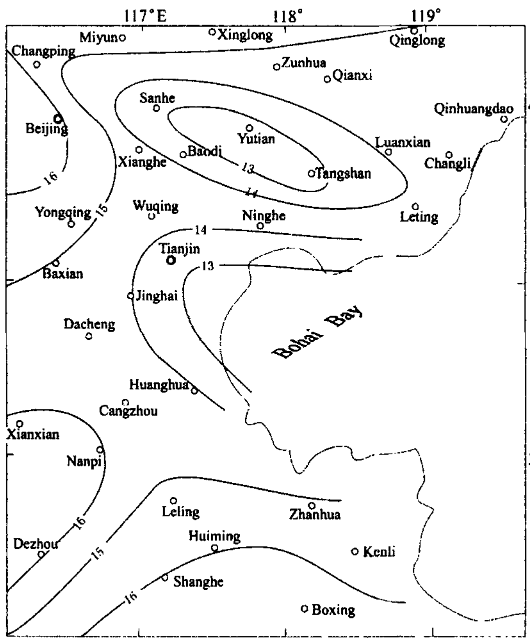

Figure 2 Depth contour map of interface C_1 in Bohai Bay and its adjacent areas

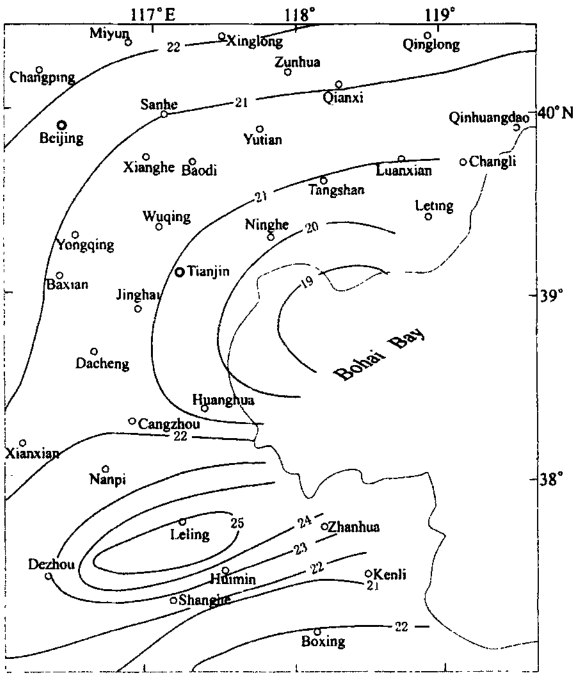

Figure 3 Depth contour map of interface C_2 in Bohai Bay and its adjacent areas

upper mantle of Bohai Bay and its adjacent areas.

2.1 Structures of the upper crust and its interfaces

This part involves the sedimentary cover and the crystalline basement under it, totaling 19~25 km in thickness. It becomes thicker from Bohai Bay northwestwards and southwestwards; it also thickens gradually northwards beyond Tangshan–Sanhe.

The upper crust consists of 4 different velocity gradient layers. a) The first layer is mainly low-velocity Cenozoic cover, with average sedimentary thickness 3 000~4 000 m in the depressions, the greatest thickness being 5 200 m in Bohai Bay of Huanghua depression. Surface velocity is 3.40~4.60 km/s in the northern mountainous area and 2.00~3.00 km/s in the plain area, the lowest being around 1.80 km/s in Bohai Bay. b) The second layer ranges from below Palaeozoic Erathem to the greatest penetrating depth of Pg wave, with average velocity 5.00~6.10 km/s. c) Velocity of the third layer is 6.10~6.25 km/s. Interface C_1 is 13~16 km deep. Figure 2 shows little variation in the depth of this interface, *i.e.* 13~14 km in Bohai Bay, Tianjin, Ninghe, Tangshan and Sanhe, 15~16 km in the outer areas such as Zunhua, Beijing, Baxian, Nanpi, Leling and Shanghe. d) In the fourth layer (C_1~C_2), velocity of the top surface is 6.30~6.32 km/s, and bottom surface 6.33~6.34 km/s. It is a layer with relatively weak velocity gradient, except that there are low-velocity layers (bodies) in some sections. Figure 3 shows that inter-

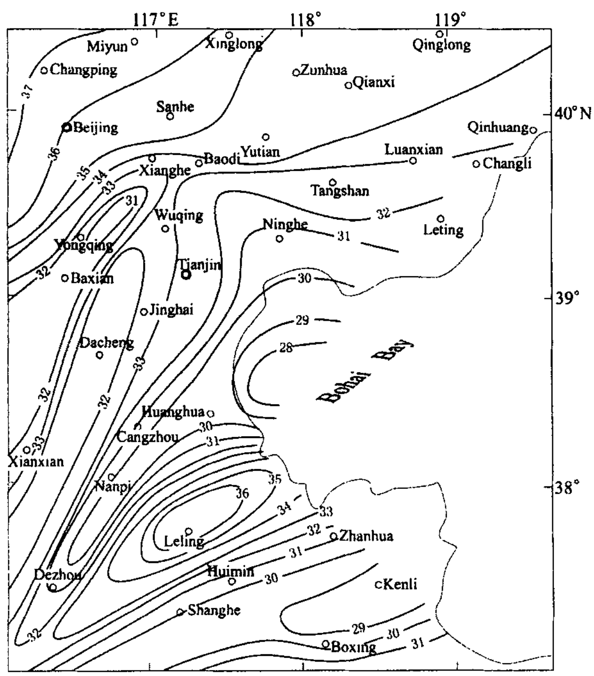

Figure 4 Depth contour map of M-discontinuity in Bohai Bay and its adjacent areas

face C_2 fluctuates a lot in this part. It is 19~20 km deep near Bohai Bay, and gradually becomes deeper westwards and northwards to 21~22 km. It deepens gradually south-westwards to 25 km near Leling and then becomes shallower further south. This layer is 6~8 km thick on the average, the greatest thickness being 10 km near Leling.

2.2 Structures of the lower crust and Moho

The lower crust is generally composed of two layers. The upper layer, 4~8 km thick between C_2~C_3, is on the whole a weak gradient layer, with a velocity 6.40~6.50 km/s. Negative velocity gradient appears in some parts of this layer. The lower layer is a strong velocity gradient layer. Only one or two profiles display inversion of velocity gradient in some sections. In the bottom part of this layer, which is 3~4 km thick and close to Moho, velocity increases rapidly from 6.60 km/s to 7.00 km/s. The lower layer, 4~6 km thick, reflects the characteristics of crust-mantle transitional zone.

As shown in Figure 4, M-discontinuity is the shallowest in Bohai Bay, *i.e.* 28 km deep. It becomes gradually deeper northwestwards to 35~36 km in Zunhua, Sanhe and Beijing, and fluctuates obviously westwards. It deepens abruptly to 36 km southwards near Leling and becomes shallow again further south to 29~30 km in Huimin-Kenli. On the whole, there is a mirror-image relationship between the deep structure of Moho and the shallow structure. The upper mantle uplifts near Yongqing in the northeast of Jizhong depression, in Bohai Bay of Huanghua depression and near Kenli of Jiyang depression. The upper mantle goes down in Tianjin-Cangxian of Cangxian uplift and near Leling of Chengning uplift. There is a contorted zone of Moho depth contour from the north side of Bohai Bay towards the northwest, which demonstrates the deep crustal characteristics of the middle section of Zhangjiakou Penglai tectonic zone.

2.3 Velocity structure of the topmost upper mantle

The average velocity of the topmost upper mantle in the studied area is 7.90~8.10 km/s, which becomes higher with the increase of depth. At 10 km below Moho, velocity gradient value is small, *i.e.*, 0.015~0.030 km·s^{-1}·km^{-1}.

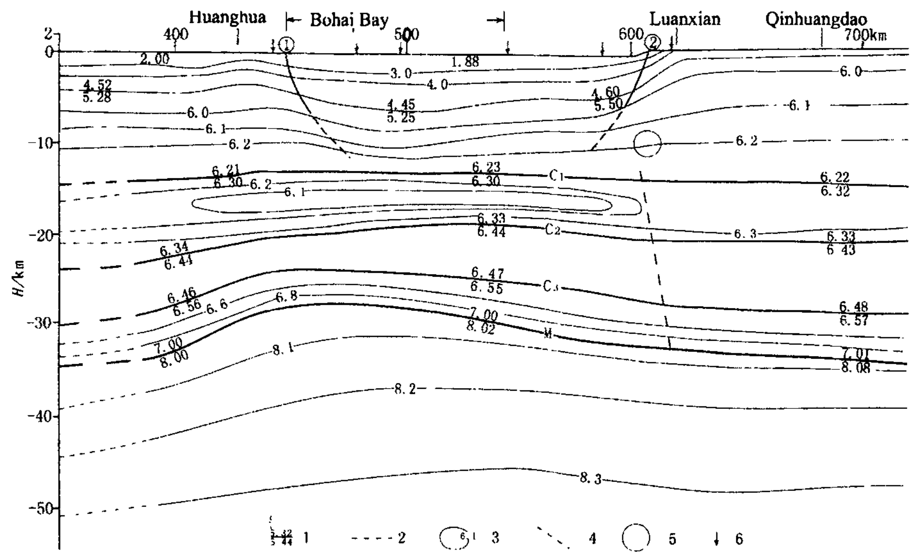

Figure 5 Crust/upper-mantle velocity structure revealed by DSS profile VIII passing through Bohai Bay

1. Seismic interfaces and velocity (km/s); 2. Inferred interfaces; 3. Velocity contour (km/s); 4. Inferred deep crustal fault; 5. Luanxian (M=7.1) earthquake; 6. Shot point position; C_1, C_2, C_3. Crustal interfaces; M. Moho-discontinuity; ① Chengxi fault; ② Ninghe-Changli fault

3 Position of deep crustal faults and distribution of crustal low-velocity layers

3.1 Position of deep crustal fault zones

Three deep crustal fault zones are inferred by DSS data acquired in Bohai Bay and its adjacent areas. They are Xianghe-Ninghe-Changli fault zone, Tangshan fault zone and Cangzhou-Tianjin-Ninghe fault zone (Figure 6).

3.1.1 The Xianghe-Ninghe-Changli fault zone

This fault zone is inferred by DSS data from *H*-06, *H*-02, VII and VIII profiles and is based on 2-D results. Seismic records from the east section of SP275.0 show that Pm waveforms differ obviously on the two sides of post 393 km: Pm wave is strong on the western side, whereas it is weak and unstable on the eastern side. These records reveal the crustal structure of Xianghe and its vicinity. Besides, 2-D results show that this is the area where M-discontinuity fluctuates significantly (LI, *et al*, 2001; ZHAO, *et al*, 1999). The receiving points No. 59 and No. 61 of SP35.86 on the *H*-02 profile, which reveals the fault zone, recorded that Pm wave is extremely weak and shows a travel-time delay of 0.16 s. 2-D results indicate that M-discontinuity is shallow in the south and deep in the north, with an offset of 1.2 km. There is an obvious low-velocity (6.10 km/s) body in the upper crust north of post 245 km on profile VII, where C_1, C_2, M-discontinuity and their depth contours fluctuate considerably. Another low-velocity body (6.10 km/s) exists obviously in the upper crust south of post 600 km on profile VIII, where M-discontinuity is a transitional variation zone from shallow south to deep north.

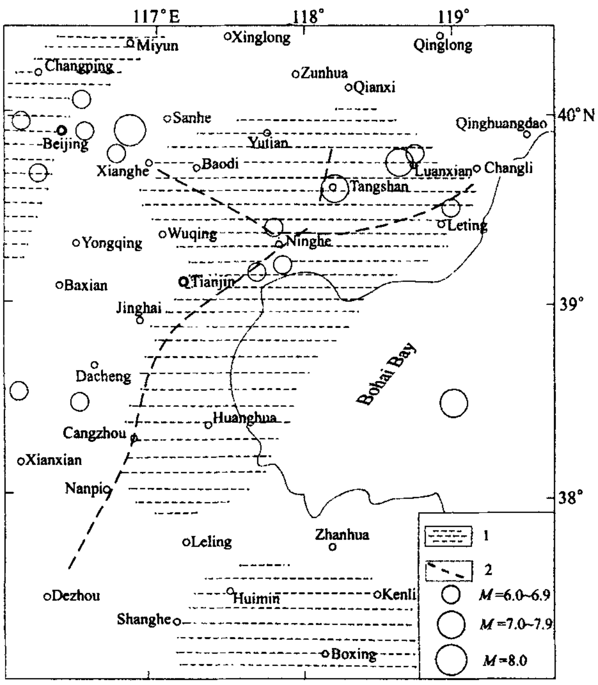

Figure 6 Distribution of deep crustal faults and upper-crust low-velocity bodies

1. Upper crustal low velocity bodies; 2. Deep crustal fault

3.1.2 The Tangshan deep crustal fault zone

Inference of this fault zone is based on the recording sections of SP32.64 on *H*-05 profile which show that an abrupt variation of Pm energy and a sudden jump of Pm travel time occur at post 137 km, suggesting a rupture of Moho near post 75 km. M-discontinuity is deep on the eastern side and shallow on the western side of the rupture, with a fault throw 3~5 km. An obvious low-velocity (5.80 km/s) body exists in the upper crust northwest of post 42 km on *H*-01 DSS profile, where C_1, C_2, M-discontinuity and the depth contours fluctuate greatly (ZENG, *et al*, 1985).

3.1.3 The Cangzhou-Tianjin deep crustal fault zone

This fault zone is inferred on the basis of results from L_4, III, L_2, H-04 and VII profiles. 2-D results from L_4 and L_2 profiles show that M-discontinuity fluctuates at post 260 km on L_4 and at 270 km on L_2. A low-velocity (6.10 km/s) body is found in the upper crust on its eastern side. 3-D inversion reveals a fault throw of about 2 km here (ZHANG, *et al*, 1998). C_1, C_2, M-discontinuity and the depth contours fluctuate distinctly near post 150 km, and there is a low-velocity (6.00 km/s) body in the upper crust on the eastern side of the fault. Seismic records from receiving points 39, 41 and 43 of SP233.142 on profile VII, which also reveals the fault, demonstrate weak Pm wave and disorderly wave groups. 2-D results show obvious fluctuation of the crustal interfaces and M-discontinuity.

3.2 Distribution of crustal low-velocity layers

Distribution of crustal low-velocity layers (bodies) (Figure 6) is determined on the basis of 2-D data processing and interpretation on some of the 14 DSS profiles passing through the studied area, and by synthesizing previous results by other scientists (SUN, *et al*, 1988; ZHANG, *et al*, 1998; LI, *et al*, 2001)

1) The Huimin-Boxing-Kenli low-velocity zone. The top surface of this low-velocity layer (body) is 12~16 km deep and bottom surface 20 km deep, with a velocity 5.90~6.20 km/s, which differs from that of the adjacent formation by 3%~6%.

2) The Huanghua-Ninghe-Luanxian low-velocity zone. This is a large low-velocity layer (body). In the south, its top surface is 12~14 km deep and bottom surface 17~22 km deep, with a velocity of about 6.10 km/s, which differs from that of the adjacent rock by 3%; In the north, the top surface is 9~14 km deep and bottom surface 16~22 km deep, with an average velocity of 6.10~6.20 km/s, *i.e.* 3%~4% different from that of the adjacent rock.

3) The Miyun-Changping-Fangshan low-velocity zone. The top surface of this low-velocity layer (body) is 8~11 km deep and bottom surface 13~15 km deep, with a velocity 5.90~6.10 km/s, which differs from that of the adjacent rock by 3%~5%.

4 Discussion and conclusions

1) Deep crustal tectonic features of Bohai Bay and its adjacent areas revealed by the 14 wide-angle reflection/refraction profiles are as follows. a) There is an obvious crustal thickness variation zone from Bohai Bay northwestwards to Beijing-Changping, where the depth contours of Moho contort (Figure 4). It coincides with the middle section of Zhangjiakou-Penglai fault (ZHANG, *et al*, 1998). The Tangshan M=7.8 earthquake in 1976 and the Sanhe-Pinggu M=8.0 earthquake in 1679 took place right in this crustal thickness variation zone, suggesting that noticeable variation in crustal thickness has a bearing on the development and occurrence of earthquakes. b) The upper mantle uplifts near Yongqing in the northeast of Jizhong depression, in Bohai Bay of Huanghua depression and near Kenli of Jiyang depression, where crustal thickness is 31 km, 28 km and 29 km, respectively. Near Leling of Chengning uplift, there is a depression of the upper mantle, where crustal thickness is as great as 36 km. The uplift and depression structure of this area has a mirror-image relationship with its shallow structure.

2) Thickness of the upper crust in the studied area varies a lot. It becomes gradually greater northwards and northwestwards from 19~20 km in Bohai Bay to 21~22 km in Changping, Zunhua and Qinglong. It turns greater rapidly southwestwards to 25 km near Leling. The upper part of the upper crust is 13~16 km thick. The area including the neighborhood of Bohai Bay and Baodi-

Tangshan is relatively an uplifted area, which is 13 km thick. Figure 5 shows that, in the vicinity of Bohai Bay, the greater the Cenozoic sediment thickness is, the smaller the crystalline upper crust thickness will be, which indicates that surface subsidence in the Cenozoic Period and the total amount of sediment resulted completely from tensional fracture and lateral extension of the crystalline upper crust (LIU, 1985; LIU, *et al*, 1996).

3) Thickness of lower crust in the area ranges between 9~12 km and its bottom interface (Moho) is 28~37 km deep. The thickness and depth of the lower crust are evidently smaller below the middle-southern part of Bohai Bay in Huanghua depression than in the northern Yanshan area. As viewed from velocity structure, the upper part of the lower crust is a weak gradient layer, whose velocity is 6.40~6.50 km/s and velocity inversion occurs in some places. Its lower part, 3~4 km thick and close to Moho, is a strong velocity gradient layer, where velocity increases rapidly from 6.60 km/s to 7.00 km/s. According to domestic and foreign laboratory tests on various kinds of rock specimen under crustal temperature and pressure conditions (Holbrook, *et al*, 1992; ZHANG, SUN, 1998; GAO, *et al*, 1999), the 6.50 km/s velocity value corresponds to intermediate granulite while 6.80~7.00 km/s corresponds to basic granulite. On these grounds, we conclude that the formation of the lower crust in the area turns gradually from intermediate granulite on the top to basic granulite at the bottom. This is consistent with the variation pattern of the outcropping lower crustal formation in eastern Hebei Province north of Bohai Bay (WU, GUO, 1991).

4) Shallow offset structure develops in the studied area. According to the abrupt variations of dynamic/kinetic characteristics of seismic waves (*e.g.* travel-time jump and amplitude energy variation) and the undulation of 2-D velocity contours and seismic interfaces (all determined on the base of the DSS profiles in the area), three deep crustal fault zones are inferred. All the fault zones extend to Moho and on one or two sides of these faults there are low-velocity (5.90~6.10 km/s) layers (bodies) in the lower part of the upper crust. The low-velocity layers (bodies) most probably resulted from partial melting or the existence of free water in the crust. Since the Eocene Epoch, the asthenosphere under North China plain has uplifted violently, basic magma overflowed, crust thinned, ground surface subsided steeply and the upper crust spread laterally (LIU, *et al*, 1984; TENG, *et al*, 1997). Thermal activities and lateral movements as well as the existence of free water, caused partial melting in the lower part of the upper crust of the Cenozoic depression in the studied area. The low-velocity layers (bodies) may be closely related to the development and occurrence of earthquakes. The state of temperature and pressure here corresponds to the brittle-ductile transitional zone of rocks, while the overlying rocks feature brittle deformation, whose strength reaches the maximum. Though stress is not liable to concentrate in the low-velocity layers (bodies), yet they are the possible places for large strain accumulation. Therefore, it is evident that such tectonic setting contributes to rock ruptures on the top, and the occurrence of earthquakes.

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