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# 2-D P-wave velocity structure in the mideast segment of Zhangjiakou-Bohai tectonic zone: Anxin-Xianghe-Kuancheng DSS profile*

WANG Fu-yun[1] (王夫运) ZHANG Xian-kang[1] (张先康) CHEN Yong[2] (陈 颙)
LI Li[2] (李 丽) CHEN Qi-fu[2] (陈棋福) ZHAO Jin-ren[1] (赵金仁)
ZHANG Jian-shi[1] (张建狮) LIU Bao-feng[1] (刘宝峰)

1) *Geophysical Exploration Center, China Earthquake Administration, Zhengzhou* 450002, *China*
2) *Institute of Earthquake Science, China Earthquake Administration, Beijing* 100036, *China*

**Abstract**

In order to get the 3-D fine velocity structure in the Capital-circle area of China, 6 explosions, ranging from 1800 to 2500 kg, were conducted and recorded by an array of 240 seismographs. A reflection/refraction survey was carried out along the profile extending from Anxin county, Hebei Province northeastward to Yanshan Mountains, crossing the Zhangjiakou-Bohai tectonic zone. The 2-D velocity structure of P wave was imaging along the profile. The results show that abnormality exists in the deep structure of the Zhangjiakou-Bohai tectonic zone: The basement is significantly depressed, the interfaces and Moho are uplifted, and a strong velocity gradient layer is existed above the Moho that may be dislocated by deep fault. The crust of Huabei basin is thin and low velocity body exists in the crust. The Yanshan Mountains' crust is thick, the layers in the crust are quite clear and the velocity in the layer is homogeneous. Huabei basin differs from Yanshan Mountains in structure.

**Key words**: **2-D P-wave velocity structure; artificial explosion; Capital-circle area of China; Zhangjiakou-Bohai tectonic zone; crust-mantle transition zone**
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## Introduction

The Capital-circle area is the center of politics, economy and culture of China, and many strong earthquakes occurred here in history. The Zhangjiakou-Bohai tectonic zone located in the area is an important active zone. In the period of 500 years between AD 1481~1981, 18 earthquakes with magnitude more than 6 occurred in the area and 11 of them lay in this active tectonic zone. During 1992~2001, continuous GPS observation found sinistral relative movement between Yanshan Mountains and Huabei basin (YANG, *et al*, 2002). More and more studiers are interested in the deep structure of Zhangjiakou-Bohai tectonic zone, in which both Cenozoic tectonic motion and seismicity are very intensive and frequent (SUN, *et al*, 1988; ZHANG, *et al*, 1996, 1998; ZHANG, *et al*, 2002a; ZHAO, *et al*, 1999; HE, *et al*, 1998; LIU, 2001).

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In order to probe into the fine crustal structure, active tectonics and deep earthquake-related tectonics setting, the project of Fine Crustal Structures and Tectonic Movement Based on a Dense Seismic Digital Networks and Arrays in the Capital-circle Area funded by the Ministry of Science and Technology was conducted in April, 2002. 6 explosions, ranging from 1800 to 2500 kg, were made at Dahuangzhuang in Huailai county, Ping'ancheng in Zunhua county, Jianzigu in Fengnan county, Xinji in Sanhe county, Jiuzhou in Anci county, and Santai in Anxin county, respectively. Among them, 4 shots and 100 seismometers located on the same profile constitute a wide-angle reflection/refraction profile. The wide-angle reflection/refraction data are used by a ray tracing algorithms for 2-D complex structure to produce an image of velocity variations in the crust. Based on the result, we discuss the questions related to the deep structure of Zhangjiakou-Bohai tectonic zone and make a comparison with the previous deep seismic sounding (DSS) results.

In the Capital-circle area of China and its adjacent regions, 8 DSS profiles were completed from 1976 to 1984. Among them, 2 profiles are perpendicular to this one and 2 profiles are nearly parallel to this one. ZHANG, *et al* (1996) investigated the fine deep structure of Zhangjiakou-Bohai tectonic zone using these data. The results show: ① Zhangjiakou-Bohai tectonic zone is about tens kilometers wide, both the interfaces and Moho are deformed remarkably, and there exists low velocity body in the crust. The result from electromagnetic sounding also reveals the activity of Zhangjiakou-Bohai tectonic zone extending from the crust to the lithosphere. ② Zhangjiakou-Bohai tectonic zone is not straight to the upper mantle, and the upper crust is decoupled from the lower crust in the southwestern area. ③ The tectogenesis of Zhangjiakou-Bohai tectonic zone is down to the lithosphere.

# 1 Geological setting and location of profile

The survey line traverses Huabei basin and Yanshan Mountains from the southwest to the northeast, passing through Baoding depression, Rongxian swell, Gu'an depression, Beijing-Tianjin depression, and Yanshan uplift. There are deposits of Mesozoic strata and Cenozoic strata in Huabei basin and their thickness is markedly different. On the north of the proximate EW-trending Bodi fault, the strata of Sinian System are exposed or covered by Cenozoic strata (Compiling Group of *Achievements from Deep Geophysical Exploration* of State Seismological Bureau, 1986).

The wide-angle seismic reflection/refraction profile of Anxin-Xianghe-Kuancheng, extending from Zhaili in Anxin county northeastward to Dangba in Pingquan county, is about 320 km in length. There are 4 shots along the profile, which are located at Santai in Anxin county, Jiuzhou in Anci county, Xinji in Sanhe county, and Ping'ancheng in Zunhua county, respectively (Figure 1).

An array of 100 seismographs (2-Hz 3-component seismometer with a recording length of 3 minutes) for DSS are arranged along the profile in a sparse 1~3 km receiver spacing. The source spacing is 50~80 km and the array of receivers has a length of 300 km (Figure 2). 4 explosions, ranging from 1 200~2 200 kg, were conducted along the profile. From the arrays of source points and receivers, the travel time of Pg wave on the recording sections of reversed profiling are reciprocal, and PmP reflections between continuous shots are partly covered. In order to get high-quality data, explosions were conducted at 1~4 a.m. The effective data obtained in the experiment are up to 87%.

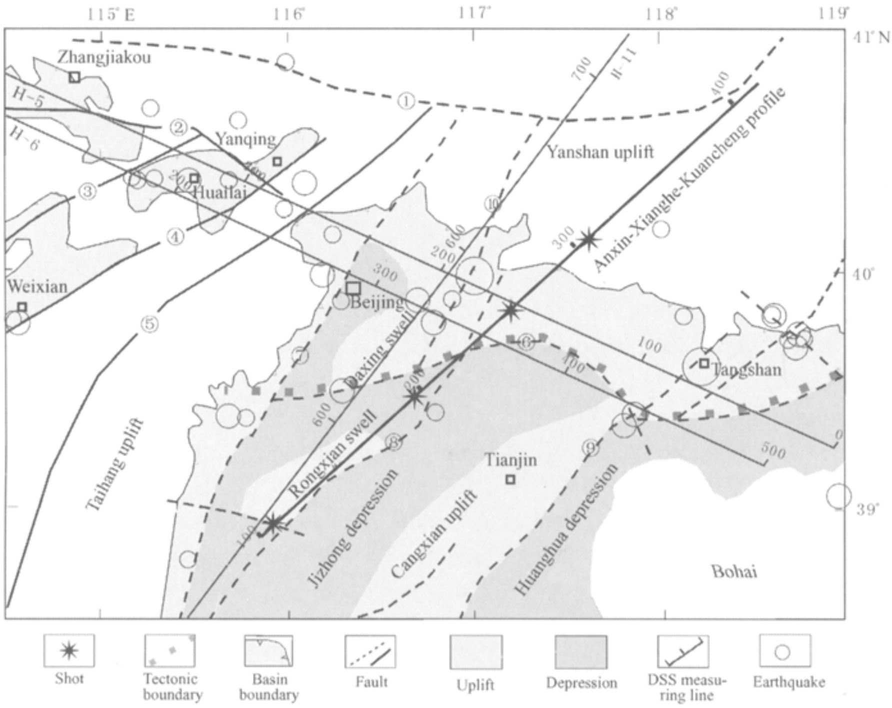


Figure 1 Geological structure and measuring line in the research area
① Zhangjiakou-Beipiao fault; ② Huaian-Xu+anhua fault; ③ Xiahuayuan fault; ④ Huaian-Weixian fault; ⑤ Zijingguan fault; ⑥ Baodi fault; ⑦ Taihangshan fault; ⑧ Hexiwu-Niudong fault; ⑨ Cangdong fault; ⑩ Xiadian fault

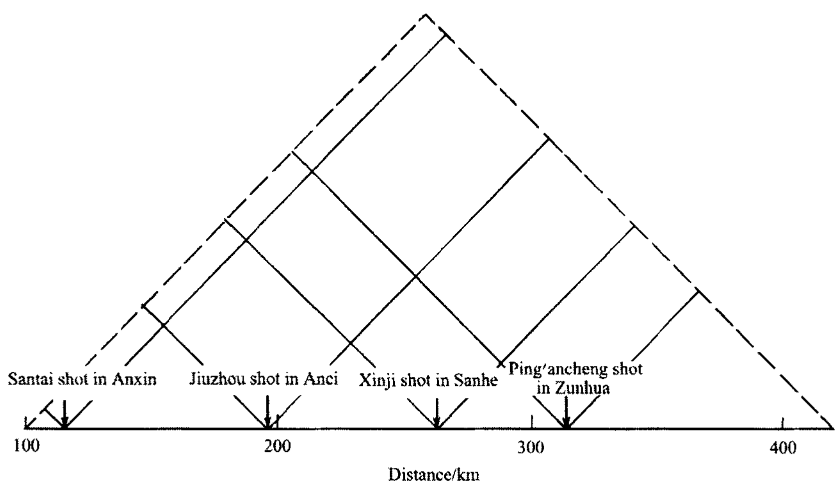


Figure 2 Observation system of longitudinal measuring line

## 2 Characteristics of wave groups

Figures 3~6 show are seismic recording sections of P wave; synthetic seismic recording sections of P wave; travel time fitting; ray tracing diagram of Anxin, Anci, Sanhe and Zunhua shots, respectively.

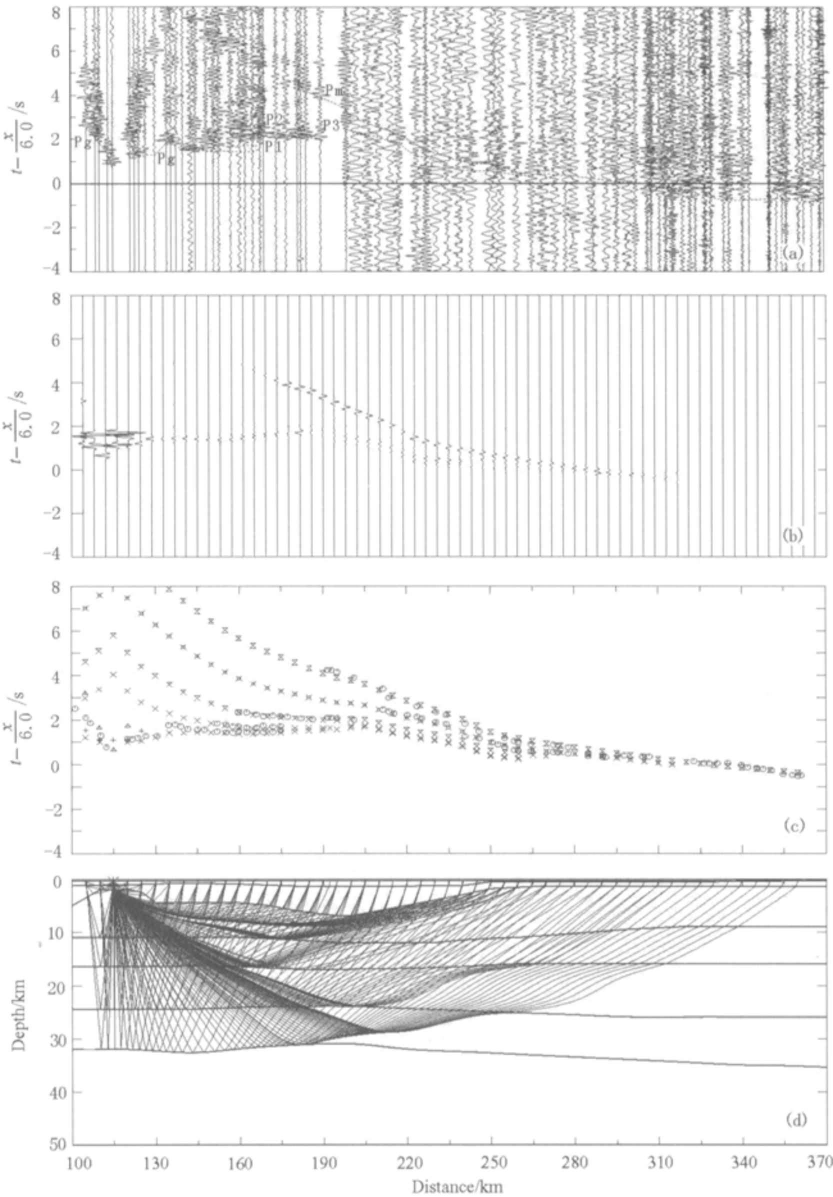


Figure 3 Comprehensive interpretations for Anxin shot along Anxin-Xianghe-Kuancheng profile
(a) recording section; (b) synthetic seismic recording; (c) travel time fitting; (d) ray tracing diagram

1) Characteristics of surface wave From 6 seismic recording sections of P wave at 4 shots, we can see clearly the surface wave on the northern seismic recording section of Anxin shot, two sections of Anci shot and southern section of Sanhe shot, but the surface wave are not seen on the northern section of Sanhe shot and two sections of Zunhua shot. It shows that the Cenozoic strata of low velocity has a reasonable thickness on the south of Sanhe shot, and the basement is buried shallowly on the north of Sanhe shot.

2) Characteristics of Pg wave Pg wave is a diving wave from the upper crust or the reflected wave from the top of the basement. Its travel time curve or slope reflects the velocity structure of sediment and basement.

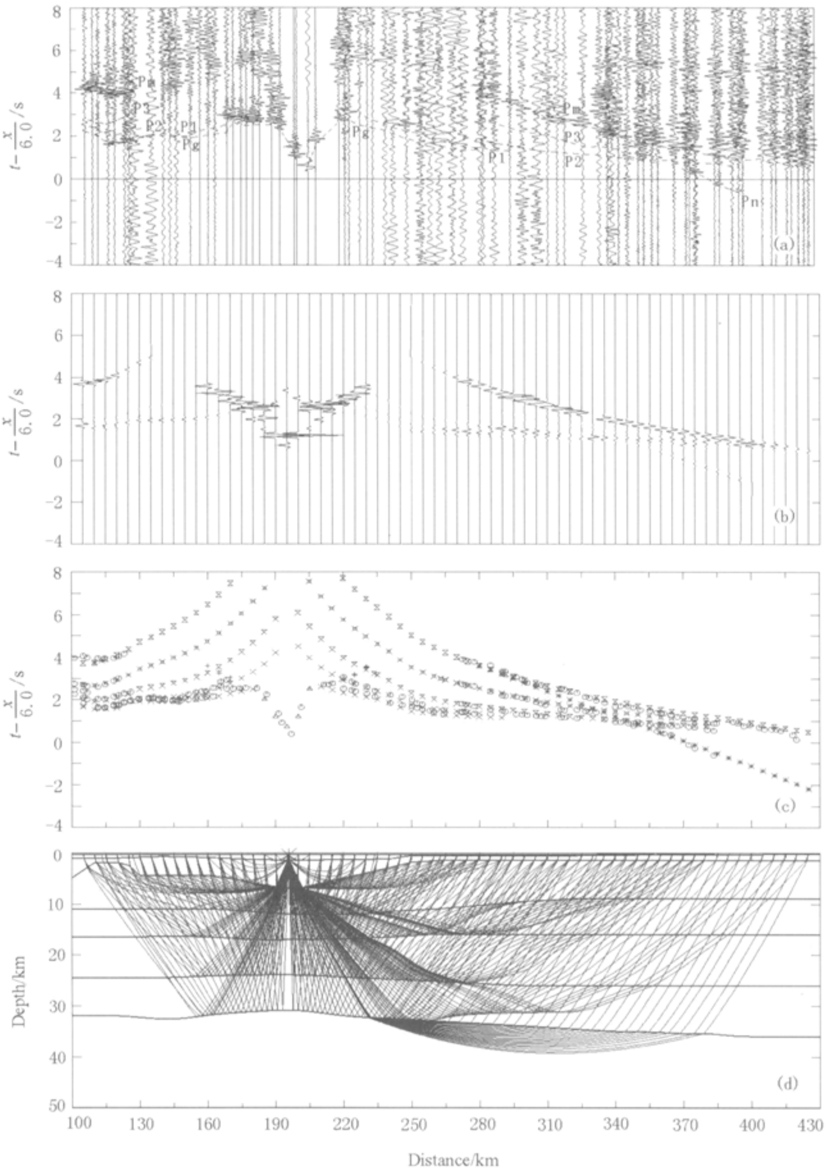


Figure 4 Comprehensive interpretations for Anci shot along Anxin-Xianghe-Kuancheng profile
(a) recording section; (b) synthetic seismic recording; (c) travel time fitting; (d) ray tracing diagram

On the south of Sanhe shot, Pg wave has a large time delay, low apparent velocity, weak energy and varying amplitude. Its traceable distance is less than 90 km and its travel time curve is convex. It reflects that the sediment cap of Huabei basin is thick and the velocity on the top of basement is low. On the north of Sanhe shot, contrarily, Pg wave has a small time delay, high apparent velocity, great energy, large traceable distance, and nearly horizontal curve of travel time. It shows that Yanshan Mountain has a very thin sediment cap and the velocity of basement is high.

3) Characteristics of intra-crust reflection The reflections of three groups are distinguished on these recording sections: $P_1$, $P_2$ and $P_3$. $P_1$, $P_2$ waves have quite strong energy on the recording sections of Anxin and Anci shots and the southern one of Sanhe shot. The traceable distance and

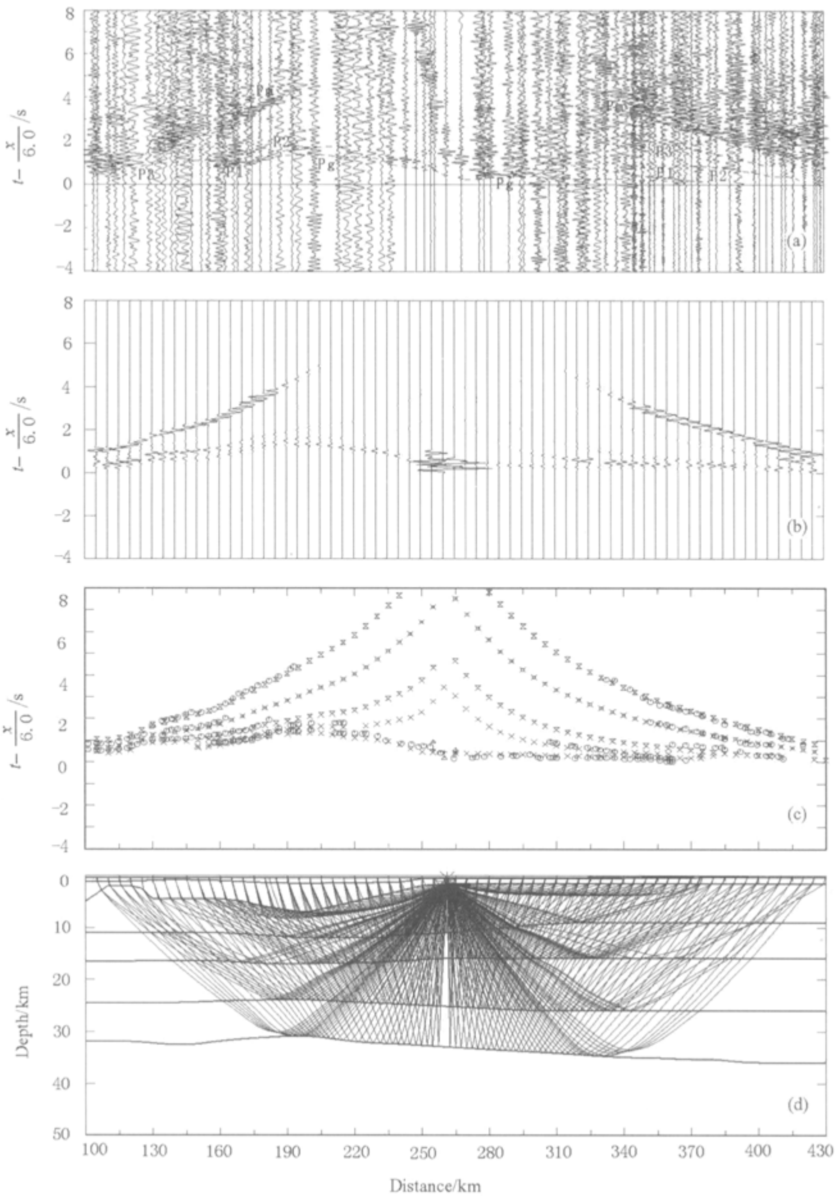


Figure 5 Comprehensive interpretations for Sanhe shot along Anxin-Xianghe-Kuancheng profile
(a) recording section; (b) synthetic seismic recording; (c) travel time fitting; (d) ray tracing diagram

travel time curves′ configuration of the two waves vary greatly with sediment thickness. $P_1$ and $P_2$ waves are unclearly distinguished on the recording sections on the north of Sanhe shot and on the south of Zunhua shot. The difference between $P_1$ and $P_2$ waves at both sides of Sanhe shot shows that Huabei basin differs greatly from Yanshan Mountains in the upper crustal structure. $P_3$ wave, emerging 0.5 s before PmP wave with a distance over 140 km, having weak energy and being named forerunner of PmP wave, is distinguishable on the northern recording sections of Anxin and Anci shots, two sections of Sanhe shot, and southern section of Zunhua shot.

4) Characteristics of Moho reflection or/and crust-mantle transition zone reflection Moho

reflection is the most marked wave among all waves on the recording section. Moho reflection often emerges in the range of 70~80 km on all recording sections except for the one of Zunhua shot. Moho reflection of Zunhua shot appears earlier because ① the velocities between both sides of Moho boundary differ greatly; ② the average velocity of crust is high. The configuration of travel time curve is subject to shallow sediment. $P_3$ wave, emerging 0.5 s before PmP wave, having weak energy and high frequency, is from crust-mantle transition zone. $P_3$ wave is not seen on the northern recording section of Zunhua shot.

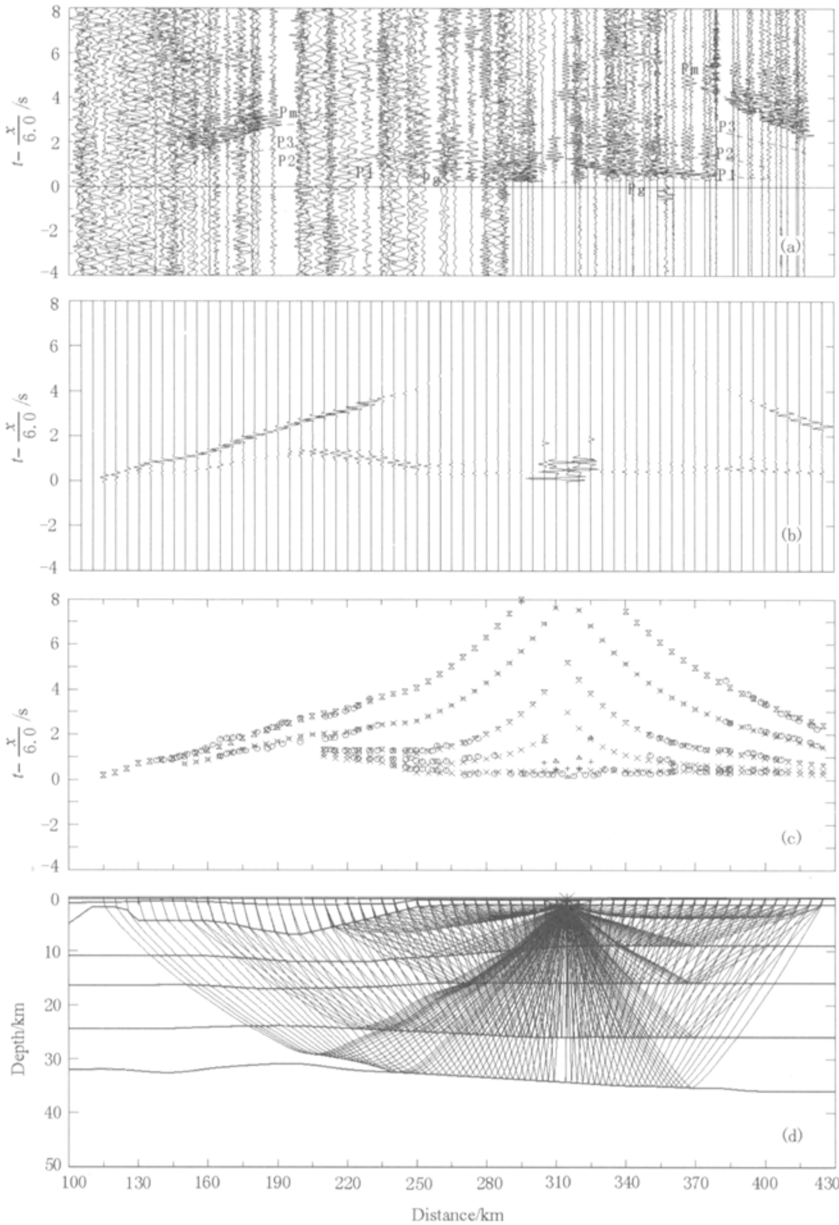


Figure 6 Comprehensive interpretations for Zunhua shot along Anxin-Xianghe-Kuancheng profile
(a) recording section; (b) synthetic seismic recording; (c) travel time fitting; (d) ray tracing diagram

5) Pn wave from the top of upper mantle Pn wave is the head wave from the top of upper mantle. It has high apparent velocity and becomes the first wave beyond the range of 150 km. Its curve of travel time is nearly a straight line. It is only distinguished on the northern recording section of Anci and Sanhe shots because of its weak energy and high noise caused by human activities.

6) Multiple wave A group of waves parallel to PmP wave emerges 3.5 s after PmP wave with a distance of 150~210 km on the northern recording section of Anci shot. As a result of travel time modeling, the wave is interpreted as multiple wave that reflects first from the top of basement to the surface, then propagates down to the Moho, and finally reflects off from the Moho to the surface.

# 3 2-D velocity structure along the profile

The 2-D model of velocity structure is mainly built up based on the interpretation of travel time data. After the same wave group is confirmed on the seismic recording section, the travel time data of each wave group are picked up. The travel time data is processed as follows. 1-D travel time fitting: ① the interfaces′ depth of every reflections and the average velocity of overlaying strata are determined using $t^2$-$x^2$ algorithm; the travel time data of Pg wave is inverted in order to get the velocity structure of upper crust using WH algorithm. ② On the basis of the results obtained by $t^2$-$x^2$ algorithm and WH algorithm, a 1-D initial model is built up in order to determine the velocity-depth function corresponding to each recording section by repeated trial-and-error fitting to the travel time data of all wave groups. 2-D travel time fitting: ① the finite-difference travel-time tomography is used to invert the travel time of initial Pg to obtain the 2-D velocity structure of the upper crust. ② The relief of crustal basement is gained using "time term" method. ③ In the light of previous two steps, the first 2-D model is set up, then the travel time data and amplitude of all wave groups are modeled using 2-D ray tracing in the complicated medium after the 1-D model and model gotten from "time term" method. The above process is repeated until a satisfied fitting is gotten. From Figures 3~6 we can see that the fitting of travel time and amplitude is satisfactory. Figure 7 reveals the layering structure of crust and upper mantle showing strong heterogeneity. The $C_2$ interface is taken as the boundary of the upper and lower crusts.

## 3.1 Upper crust

The upper crust consists of three layers (Figure 7). In the plain area, the surface layer is Cenozoic loose sediment with a velocity of 2.0~3.0 km/s, a depth of 2~3.5 km, and the maximum depth of about 6 km near Anci. In the area north to Xianghe, the surface layer is thin sediment whose velocity is 3.0~4.5 km/s and the depth is 100~300 m. The second layer consists of strata of Sinian System and metamorphic rock of crystal basement. Its velocity range is 4.5~5.6 km/s, its thickness is 2~3 km, and the gradient of velocity is quite big. The velocity and thickness of the third layer range from 5.9 to 6.2 km/s and 4 to 9 km, respectively. The bottom of the upper crust is $C_1$ interface, the depth of its southern segment rises gently from 13 km to 10 km from the south to the north. The depth of its northern segment rises sharply to 9 km. The fourth layer, the top velocity of the layer is 6.30~6.31 km/s and the bottom velocity is 6.30~6.33 km/s, is a homogeneous layer that lies between $C_1$ and $C_2$. The thickness of the layer is only 4 km near Xianghe and amounts to 10 km to the north of Zunhua. $C_2$ is about 17 km at the coordinate 240 km on the southern profile, uplifts to 14 km between the coordinate 240 and 280 km, and descends to 19 km on the north of the coordinate 280 km. $C_2$ may be an important interface in the crust, which is a sign of crust transition from brittleness to ductility (ZHANG, *et al*, 1996).

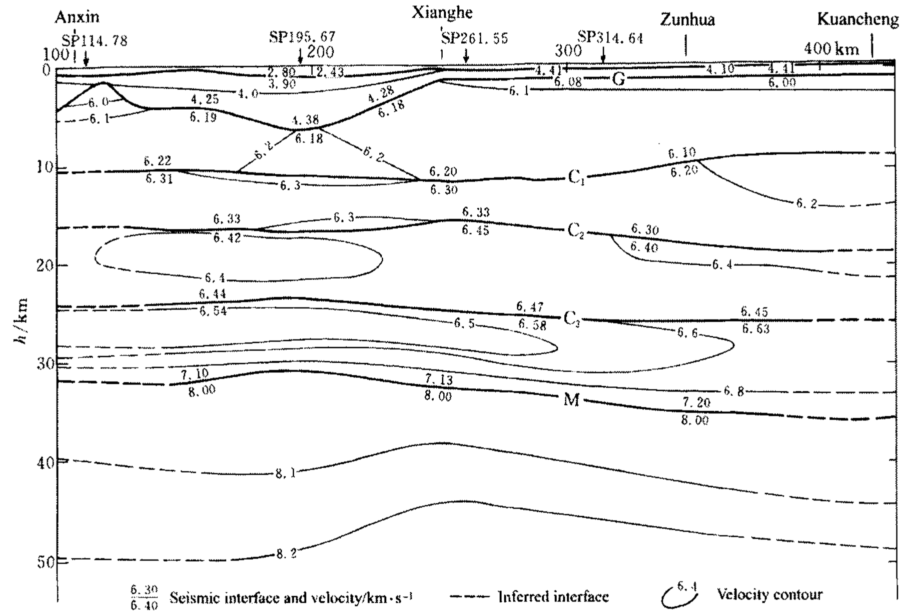


Figure 7 2-D crust-mantle velocity structure along Anxin-Xianghe-Kuancheng deep seismic sounding profile

### 3.2 Lower crust

The two sub-layers constitute the lower crust. The upper layer, with a thickness of about 7~9 km and a velocity range of 6.4~6.5 km/s, a comparatively high velocity underneath Sanhe shot and to the north of the shot, and smaller velocity gradient, is a layer between $C_2$ and $C_3$. The lower layer can be sub-divided into two layers according to the distribution of velocity gradient. The upper sub-layer is about 5~6 km thick. The variation of velocity in traverse and vertical is not big. The lower sub-layer is about 3~4 km thick, which has a very great gradient of velocity in vertical with an amplitude of 6.6 km/s~7.2 km/s. The velocity in traverse does not vary greatly.

### 3.3 Moho and velocity on the top of upper mantle

The main features of Moho along the profile are uplift at the coordinate 200 km and deepening from the south to the north. The Moho is about 31 km deep on the top of uplift and local uplift amounts to 3~4 km. The velocity on the top of upper mantle is about 8.0 km/s. The apparent velocities calculated from Pn wave group at the northern recording section of Anci and Sanhe shots are 7.3 km/s and 7.78 km/s, respectively. The smaller apparent velocity as compared with the true velocity indicates that Moho dips northwards.

### 3.4 Comparison with previous DSS results

The result of Anguo-Yongqing-Zunhua DSS profile that is parallel and nearly coincident to this profile, reveals the Moho is uplifted and 31 km deep underneath the Anguo's depression. The Moho deepens along the profile northwards and is dislocated beneath Bodi fault trace (Compiling group of *Achievernents of Geophysical Exploration*, 1986). YUE and SONG (1988) got the 2-D velocity structure of Shijiazhuang-Kalaqin DSS profile by using modeling and travel time data of the profile: The sediment caps is 3 km thick at the deepest point in the Huabei basin and about several meters to tens meters deep in Yanshan Mountains. The surface velocity ranges from 2.0 to

2.4 km/s and 3.6 to 4.2 km/s in Huabei basin and Yanshan Mountains, respectively. The crust of Yanshan Mountains consists of two layers: the upper crust usually has low velocity layer and the lower crust has several low velocity bodies. Along the profile, the Moho's relief is not large and the depth ranges from 32.5 to 34.5 km. The Huabei basin and Yanshan Mountains differ largely in structure.

This experiment has distinguished several reflection wave groups and got a fine crustal structure. The tectonic boundary of Huabei basin and Yanshan Mountains is Baodi fault trace. In the Huabei basin, the crustal thickness is 30~32 km, the crustal layering is not significant, and there are low velocity bodies in the crust; while in the Yanshan Mountains, the Moho is buried between 33~36 km, the crustal layering is clear, and there are not low velocity bodies in the crust. Near the boundary of Huabei basin and Yanshan Mountains, there is a 3~4 km wide strong velocity gradient layer.

The deep seismic reflection profiling in the area of Sanhe-Pinggu great earthquake reveals a 1~2 s wide zone of reflectivity that can only be traced laterally in a piecewise fashion (ZHANG, *et al*, 2002b). The results coincide with the 3~4 km wide strong velocity gradient layer.

## 4 Discussion and conclusions

The NE-striking Anxin-Xianghe-Kuancheng seismic wide-angle reflection and refraction profile, crossing the mideast segment of Zhangjiakou-Bohai tectonic zone, reveals the crustal structure of this significant seismically active zone.

Baodi fault is the boundary of Huabei basin and Yanshan Mountains. On the south side of the boundary, the crust of Huabei basin is about 30~32 km thick and the average velocity of the crust is about 6.1~6.2 km/s. The upper and lower crusts are rather thin, the inter-layer lateral velocity varies largely, and there are several low velocity bodies. The Moho and upper mantle is uplifted by an amplitude of about 3~4 km. In Yanshan Mountains, the Moho is buried in the depth of 35~36 km and the average crustal velocity ranges from 6.2 to 6.3 km/s. The upper and lower crusts are comparatively thick, the variation of lateral layer velocity is not large, there is no low velocity body in the crust and the Moho is nearly horizontal. The main feature of the crustal structure is the high geometric variation of basement and Moho along the entire profile. The lateral variation of Pn wave velocity is not large on the top of the upper mantle, which is about 8.0 km/s. This result reflects the characteristics of deep structure of coupled Huabei basin and Yanshan Mountains. The GPS measurement shows that Huabei basin moves to NE relative to Yanshan Mountains (ZHANG, *et al*, 2001). Obviously the variation of the crustal structure near Baodi fault relates closely to this crustal movement.

The 3~4 km thick layer of strong velocity gradient existed at the bottom of the crust is an obvious feature of 2-D velocity section. The velocity of this layer ranges from 6.8 to 7.2 km/s. It is guessed that this structure might result from the injection of mantle-generated materials at the bottom of the crust on the contacted part between basin and mountains (LIU, 2001). There is a 3~4 km thick crust-mantle transition zone in the basin-mountain contacted zone and the wave-group reflection is very instable, which shows that the currently active Zhangjiakou-Bohai tectonic zone has a deep geodynamic background.

Compared with previous results, the experiment in the paper has confirmed the boundary of Huabei basin and Yanshan Mountains. The Moho may be dislocated at the nearby boundary. The crustal structures of Huabei basin and Yanshan Mountains differ obviously. The $P_3$ wave groups observed on the seismic recording sections of Anci and Sanhe shots may result from the crust-mantle transition zone, and the 3~4 km wide strong velocity gradient belt at the bottom of the crust and beneath the contacted part of Huabei basin and Yanshan Mountains may result from the injection of upper mantle materials.

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## References

YANG Guo-hua, HAN Yue-ping, ZHOU Xiao-yan. 2002. New features of crustal motion in North China [J]. *Journal of Geodesy and Geodynamics*, **22**(3): 28~33 (in Chinese).

Compiling group of *Achievement of Deep Geophysical Exploration*. 1986. *Achievements of the Crust-mantle Structure in Geophysical Exploration* [M]. Beijing: Seismological Press, 20~137 (in Chinese).

HE Jian-kun, LIU Fu-tian, LIU Jian-hua, *et al.* 1998. The features of Meso-Cenozoic tectonic basin in the east portion of North China and the continental dynamic process [A]. In: CHEN Yong, WANG Shui, QIN Yun-shan *et al.* eds. *Paper Collections for Celebrating the 50th Anniversary of Academician LIU Guangding being Engaged in Geophysics* [C]. Beijing: Science Press, 618~632 (in Chinese).

LIU He-fu. 2001. The coupling system of basin and mountains and geodynamic mechanism [J]. *Geoscience*, **26**(6): 581~596.(in Chinese)

SUN Wu-cheng, ZHU Zhi-ping, ZHANG Li, *et al.* 1988. On exploration and research of the crust and mantle in North China [A]. In: Division of Monitoring and Prediction for Earthquake of China Seismological Bureau ed. *The Results of Probing the Crust and the Mantle in China* [C]. Beijing: Seismological Press, 19~37 (in Chinese).

YUE Hua-feng, SONG Zhan-long. 1988. The difference in the deep crustal structure between Yanshan Mountains and Huabei basin resulting from deep seismic sounding data [A]. In: Division of Monitoring and Prediction for Earthquake of China Seismological Bureau ed. *The Results of Probing the Crust and the Mantle in China* [C]. Beijing: Geological Publishing House, 216~226 (in Chinese).

ZHANG Cheng-ke, ZHANG Xian-kang, ZHAO Jin-ren, *et al.* 2002a. Study and review on Crust-mantle velocity structure in Bohai Bay and its vicinity [J]. *Acta Seismologica Sinica*, **15**(4): 447~455.

ZHANG Pei-zhen, WANG Qi, Freymueller J T, *et al.* 2001. The recent crustal movement and tectonic deformation in Chinese continent —The velocity fields and the active block [J]. *Science in China*. **D31**(7): 529~536.

ZHANG Xian-kang, WANG Chun-yong, LIU Guo-dong, *et al.* 1996. Study on the fine crustal structure in Yanqing-Huailai region—Deep seismic reflection profiling [J]. *Chinese Journal of Geophysics*, **39**(3): 356~364 (in Chinese).

ZHANG Xian-kang, ZHAO Jin-ren, LIU Guo-hua, *et al.* 2002b. Studying and probing the fine structure of seismic focus of Sanhe-Pinggu's great earthquake with magnitude of 8 by deep seismic reflection profiling [J]. *Earthquake Research in China*. **18**(4): 326~336.

ZHANG Xian-kang, ZHU Zhi-ping, ZHANG Cheng-ke, *et al.* 1998. Study on the crust-mantle velocity structure at Zhangjiakou-Bohai seismicity belt and its adjacent [A]. In: Editoral Board of *Study on Active Fault* and Department of Science and Technology Development of China Earthquake Administration eds. *Study on Active Fault* [C]. Beijing: Seismological Press, 1~6 (inChinese).

ZHAO Jin-ren, ZHANG Xian-kang, ZHANG Cheng-ke, *et al.* 1999. The crust-mantle tectonics and the velocity structure in Xianghe-Beijing-Zhuolu region and its adjacent area [J]. *Seismology and Geology*, **21**(1): 29~36 (in Chinese).