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Differences in lithospheric structures between two sides of Taihang Mountain obtained from the Zhucheng-Yichuan deep seismic sounding profile

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A 2-D model of lithospheric velocity structures in the southern part of the North China Craton was obtained using data from the Zhucheng-Yichuan deep seismic sounding profile. Results show that there are great differences in lithospheric structures between two sides of Taihang Mountain. In the eastern region, the lithosphere is thinner, with a thickness of about 70–80 km, while in the western region, the thickness is 85–120 km. There is a jump of the lithospheric thickness across Taihang Mountain gravity anomaly belt with a magnitude of about 30 km. P wave velocities of the lithospheric mantle and lower crust are lower in the eastern region and higher in the western region. In the eastern region, there are low velocity bodies in the middle and lower crust, while none were found in the western region. These differences indicate that the Taihang Mountain gravity anomaly belt is a belt with a abrupt change of lithospheric thickness and lithological composition. According to the Pm waveform, it can be deduced that the Moho in the eastern region is not a sharp discontinuity, but a complex transitional zone. From a preliminary analysis, it is found that the geothermal mechanical-chemical erosion could be the main mechanism causing the thinning and destruction of the lithosphere beneath the eastern side of Taihang Mountain. In addition, subduction of the Pacific Plate is an important factor which changes the properties of the lithospheric mantle of the North China Craton.

North China Craton, cratonic destruction, deep seismic sounding profile, Taihang Mountain gravity anomaly belt

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The Taihang Mountain gravity anomaly belt is no doubt the most important boundary inside the North China Craton (NCC). The variation value of the Bouger gravity anomaly across the belt is 80 m gal, and the largest gradient reaches as high as 1 mgal km^{-1} [1]. There are great differences in topography, geophysics, geochemistry, and geothermal heat flow between the two sides [2]. Many scientists believe that stretching of the lithosphere at the two sides may be controlled by different tectonic environments [3, 4]. Recently, studies on the evolution of the NCC have prompted geoscientists to begin to investigate the relationship between the formation of the Taihang Mountain gravity anomaly belt and lithospheric thinning in the eastern region. Some scientists have conducted a great amount of work, and have obtained many important results [5, 6]. However, because of the lack of direct evidence for lithospheric structures, contrasting viewpoints have been proposed, with unresolved conclusions to date. This paper presents a preliminary study of this problem based on the 2-D lithospheric structure from Zhucheng-Yichuan deep seismic sounding (DSS) profile.

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1 Position of the profile and data collection

The Zhucheng-Yichuan refraction/wide angle reflection DSS profile is located in the southern part of North China, with NWW strike and total length of nearly 1000 km. The profile crosses through Taihang Mountain in the western region of Anyang. As shown in Figure 1, from east to west the profile crosses through various tectonic units, including Liaojiao Basin, North China Plain, Taihang Uplift, Finwei Dislocation Basin, and Lüliang Uplift. Its western segment penetrates into the Ordos Block. The main fault zones crossed by the profile include the Tanlu, Lankao-Liaocheng, Taihang Mountain Front and East Ordos fault zones.

Seven shot points were deployed along the profile with charges of 2–5 t per shot. The Yichuan shot points were fired twice. Shot points are represented by arrows in Figure 1 and the related parameters are shown in Table 1. All 350 digital seismographs were deployed along the profile to record each shot. Thus, more than two thousand records in total were obtained. Because the focal point of this study was the eastern part of the NCC, we deployed the instruments along the profile with unequal spaces. Along the eastern segment of the profile (east of Taihang Mountain), the instrument spacing is shorter, about 1.5–2 km or less in some important regions. The instrument spacing is longer (3–4 km) along the western segment (west of Taihang Mountain). To obtain seismic records reflecting deep structures, the receiving distance for one single shot should be as far away as possible. So we used various methods to maximize the receiving distance to 400 km.

Figures 2 and 3 show the record sections of the Liaocheng and Anyang shot points, respectively. The charges are 2.5 and 2 t, respectively. From Figures 2 and 3, it can be seen that although the charges are not very large, the qualities of the records are quite good. This is because several methods were used, both in source exciting and in signal receiving. The maximum receiving distance reaches 400 km. In our records, besides seismic phases from the crust, such as Pg and Pm, there are also phases from the upper mantle, including Pn and PL. Pg waves are refractions in the crust, and Pm waves are reflections from the bottom of the crust (the Moho). Similarly, Pn waves are refractions in the lithospheric mantle, and PL waves are reflections from the bottom of the lithosphere. Comparatively, the amplitudes of the PL phases are smaller and their resolutions are not high. One reason for this is their much longer travel paths. Another important reason is that the bottom of the lithosphere is quite different in character from that of the crust. It is not a chemical boundary of the media, but a physical one. Thus, differences of the seismic veloci-

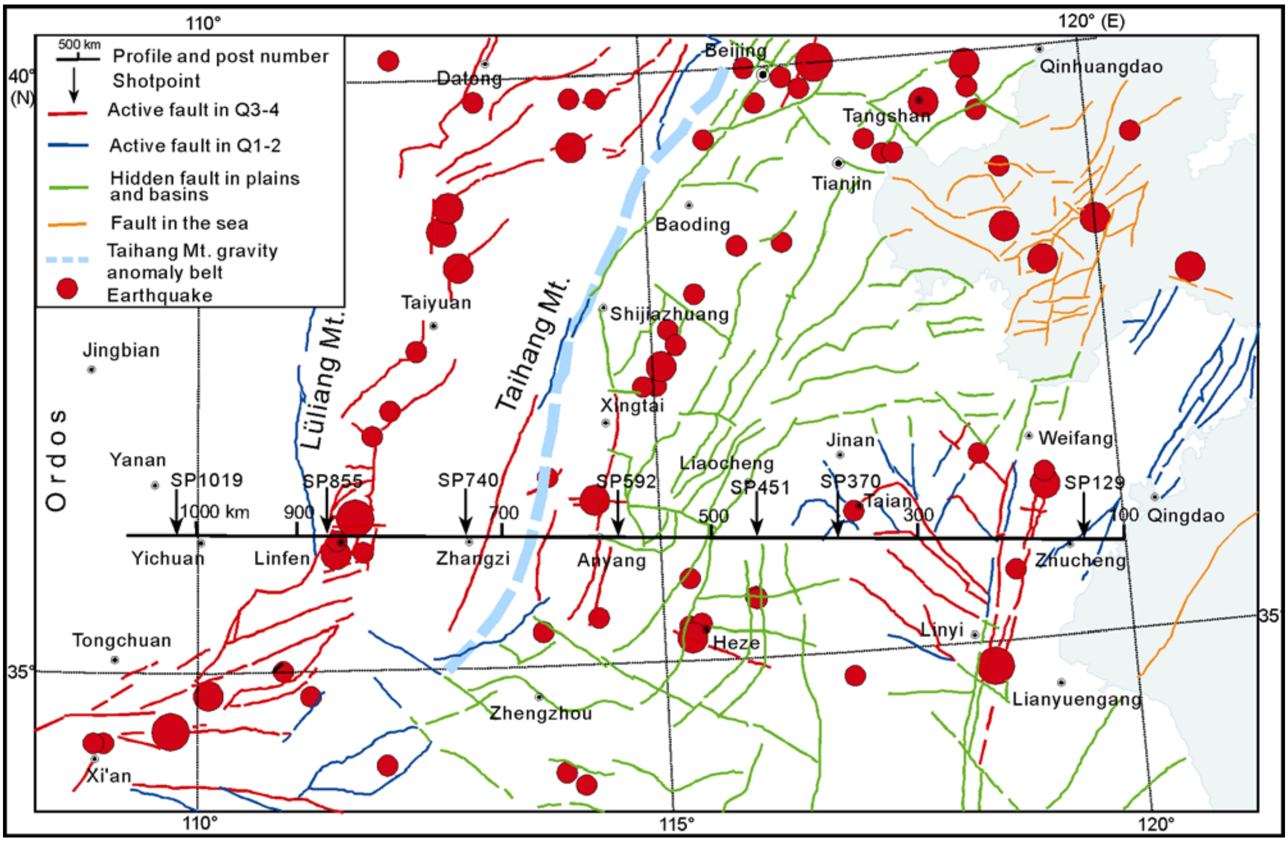

Figure 1 Geologic setting and position of the profile. Modified from ref. [7].

Table 1 Shot point parameters of the Zhucheng-Yichuan Profile

Shot point	Post number (km)	Charge (t)	Shooting time (in 2008)	Coordinate		Altitude (m)	Location
				Longitude (E)	Latitude (N)		
SP129	129.29	3.0	01:00, June 19	119°40′	36°04′	94	Zhucheng, Shandong Province
SP370	370.29	2.0	01:00, June 9	117°00′	36°04′	107	Taian, Shandong Province
SP451	451.85	2.5	01:10, June 19	116°05′	36°08′	41	Liaocheng, Shandong Province
SP592	592.30	2.0	01:00, June 24	114°32′	36°08′	80	Anyang, Henan Province
SP740	740.89	2.3	01:10, June 24	112°53′	36°13′	959	Changzi, Shanxi Province
SP855	855.07	2.0	01:10, June 30	111°36′	36°13′	441	Hongdong, Shanxi Province
SP1019-1	1019.59	4.0	01: 00, June 30	109°47′	36°07′	1203	Yichuan, Shanxi Province
SP1019-2	1019.59	1.0	02: 00, June 30	109°47′	36°07′	1203	Yichuan, Shanxi Province

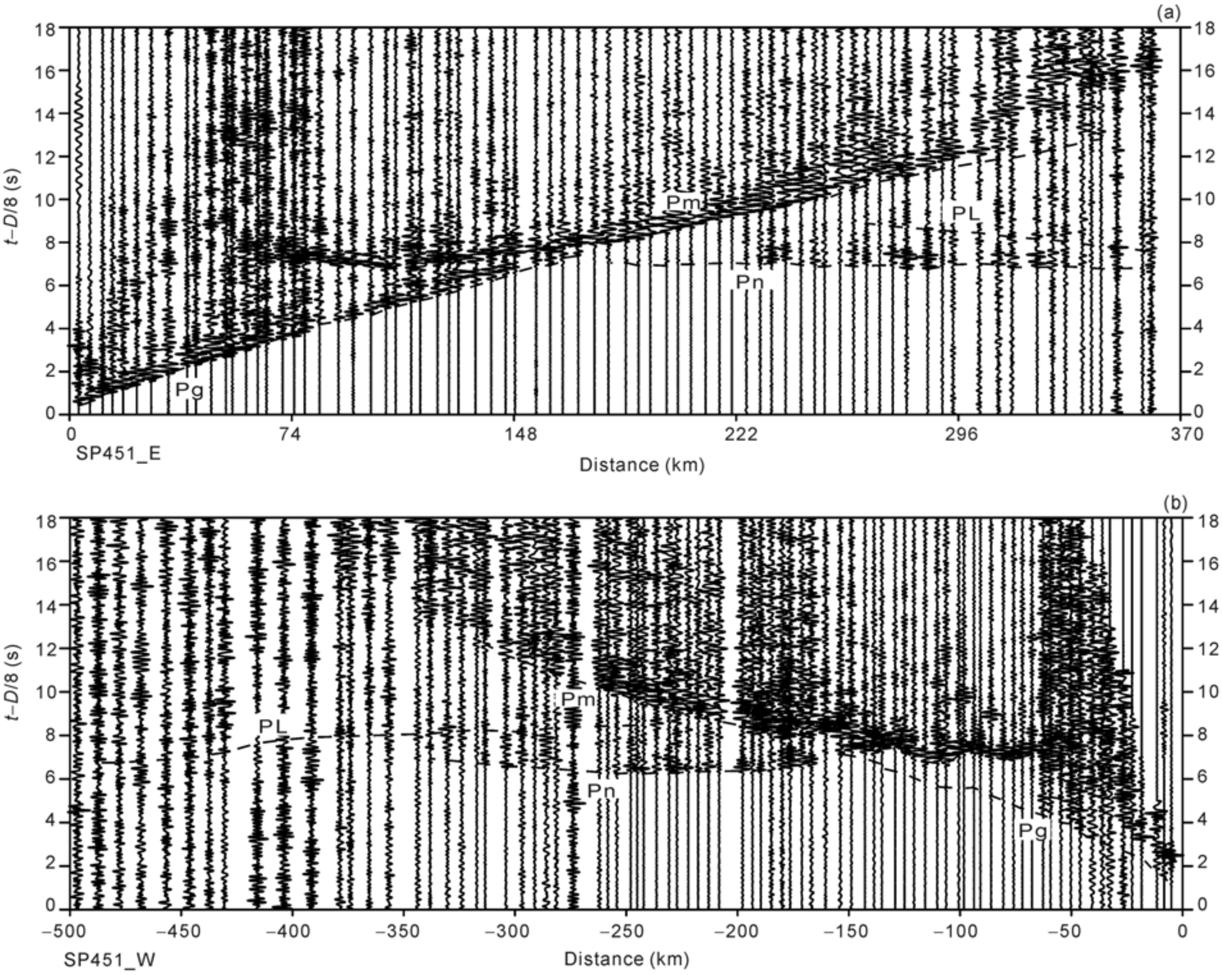

Figure 2 Seismic record section of Liaocheng shot point (SP 451). (a) Eastern branch; (b) western branch.

ties at its two sides are not so great as those at the two sides of the Moho. To identify PL phases, we focused on the shape of the travel-time curve. As reflections, the travel-time curve of the PL should belong to a concave type. Another effective method to achieve this is to make full use of our overlapping and reserved observational system formed by multiple shot points. With the interchangeability of two shot points for a reserved observational system, the reliability of the phase identification can be increased to some extent. Nevertheless, the reading precision for the PL arrivals are still lower than those for other waves. Thus, for determination of depth of the lithospheric bottom, there is an error of about 4%–6%.

2 Differences in the seismic waveforms between two sides of Taihang Mountain

In comparison with previous DSS records, all the record

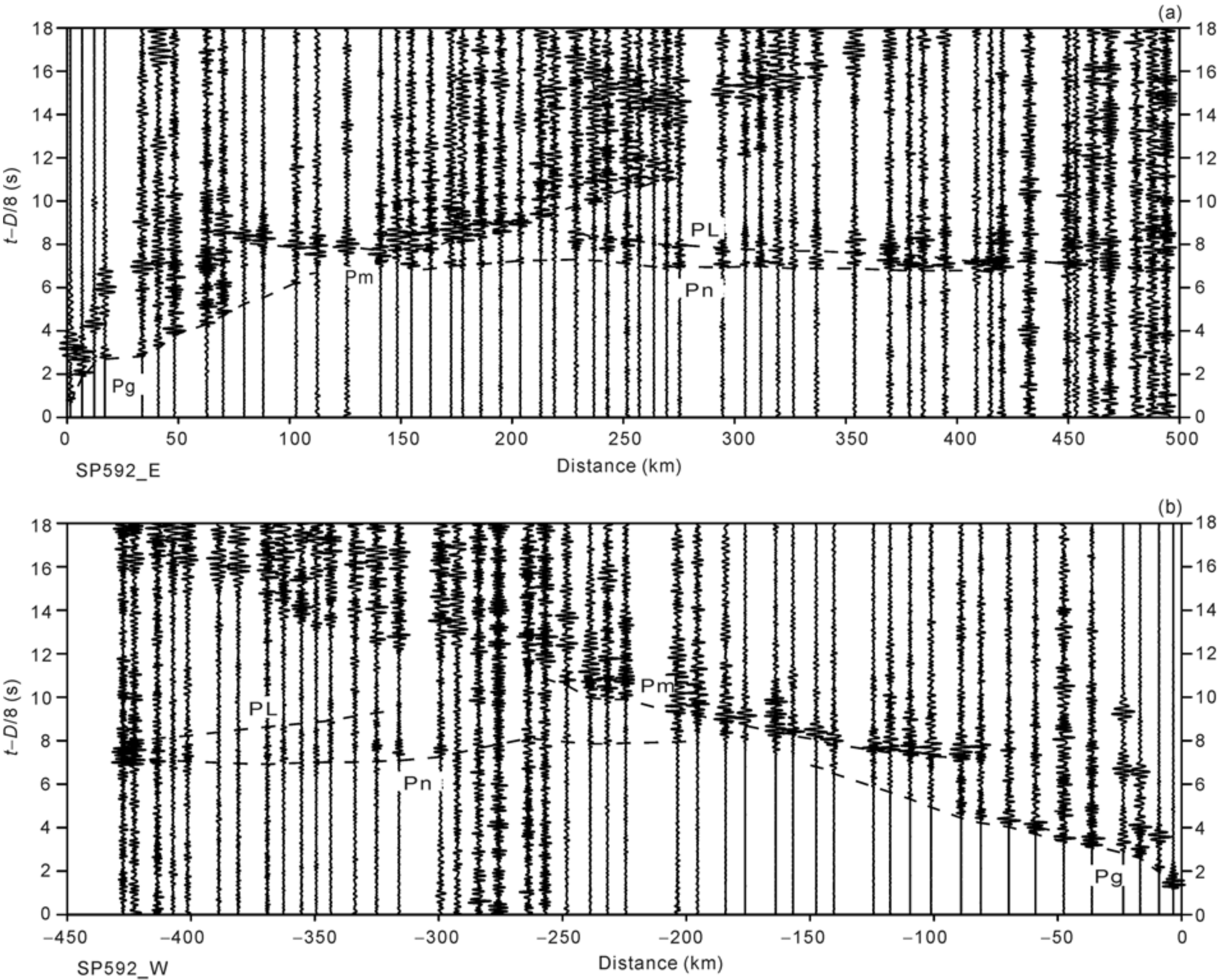

Figure 3 Seismic record section of Anyang shot point (SP 592). (a) Eastern branch; (b) western branch.

sections of the Zhucheng-Yichuan profile possessed greater receiving distances. However, when the receiving distance is great enough, the signal-to-noise ratio (S/N) will decrease rapidly. Thus, it is necessary to perform a pre-processing to the original records using newly-developed techniques for digital signal processing. Through this process the S/N of the data could be increased greatly.

The new methods used for data pre-processing are mainly based on wavelet transformation techniques, including optimal combinations of multiple components, auto-adaptive threshold noise reduction, and minimum and maximum criteria for threshold [8]. To raise the S/N as much as possible, we performed various trials for each record section. Results show that the above methods are superior to the ordinary methods based on Fourier transformation. However, for different types of phases and different record sections, the optimal method is also different. Thus, repeated tests are necessary.

Figure 4 shows an example of data pre-processing. The record sections consist of eastern and western branches of seismic records from SP Anyang. This SP is located at the boundary. Thus, the eastern and western branches of the records reflect lithosperic structures at the eastern and western sides of Taihang Mountain respectively. To highlight the reflections from the Moho (Pm), we chose the noise reduction method based on the minimum and maximum criterion for threshold. From Figure 4, it can be seen that after the noise reduction process, the Pm waves become stronger and easier to be identified .

Figure 4 also shows the great difference in Pm waveforms between the two sides of the shot point. In the western region, Pm waves are clear, and possess large amplitudes and short durations; whereas, in the eastern region Pm waves are indistinct, possess small amplitudes and long durations. Because the seismic records at the two sides were from one common explosion, the effects from the source time function on the two sides should be the same. Thus, the differences in waveforms reflect the different properties of the Moho at the two sides. Through comparison with theoretical seismograms, it can be deduced that the Moho in the eastern region has been transformed, and it is not a sharp

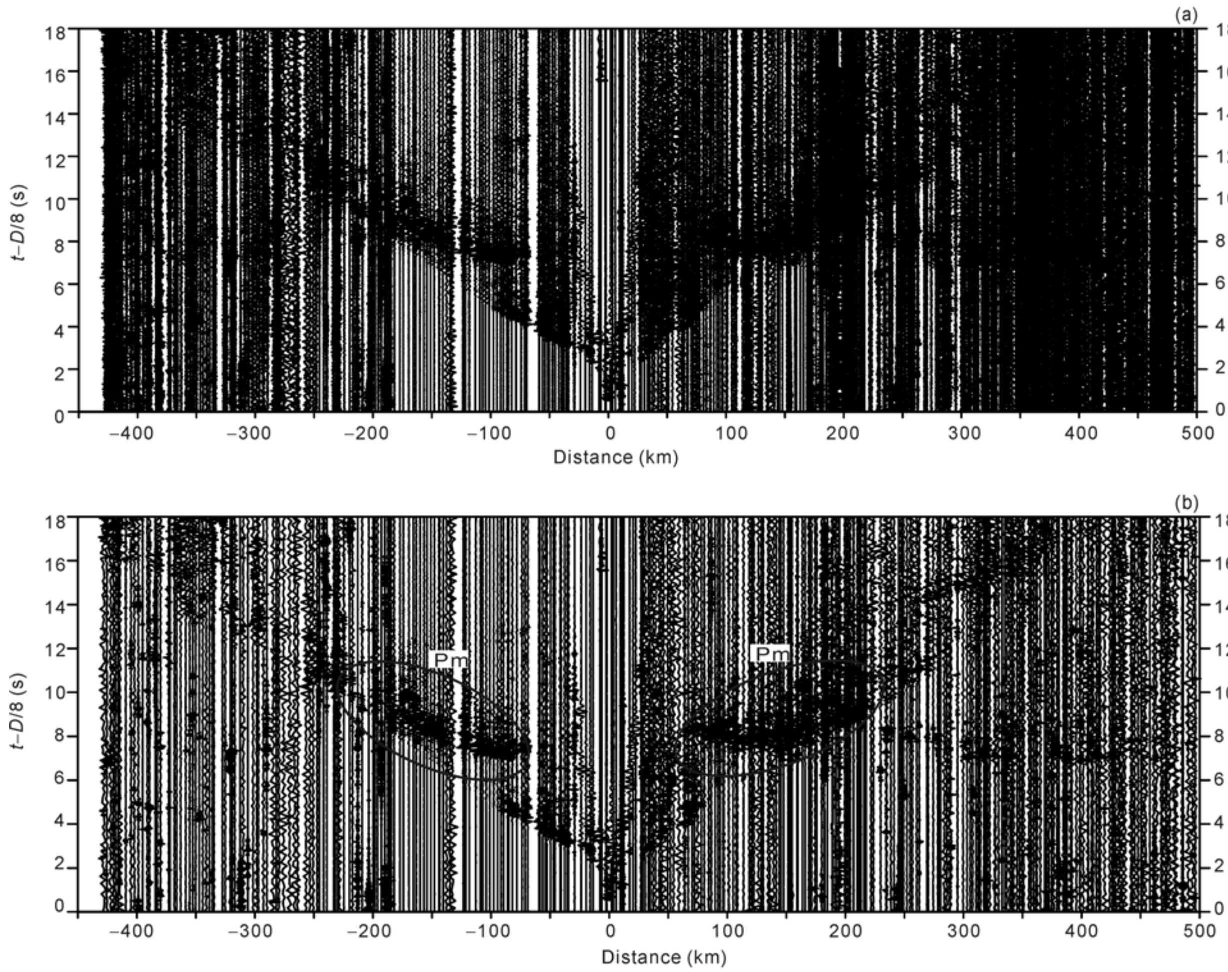

Figure 4 Application of filtering technique to record sections of SP Anyang. (a) Original seismic record; (b) seismic record filtered by wavelet transformation based on minimum and maximum criteria for threshold. Circled Pm waves are reflections from the Moho.

discontinuity, but a complex transitional zone. Comparatively, the Moho in the western region experienced slight transformations and still maintains its original feature, a sharp discontinuity.

3 Inversion of the 2-D velocity structure for the Zhucheng-Yichuan DSS profile

Based on filtering of the record sections, various seismic phases related to the crust and lithospheric mantle were identified. The main phases include refractions in the crust (Pg), refractions in the lithospheric mantle (Pn), reflections from the Moho (Pm), and reflections from the lower boundary of the lithosphere (PL), among others. The travel times of refracted waves are very sensitive to the velocity values of the corresponding layer, while those of reflected waves are closely related to the depth of the reflected boundary.

The velocity values and interface positions of the lithosphere along the profile were obtained simultaneously by seismic tomography techniques [9] using travel time data from all the SPs. In the inversion process, besides fitting between theoretical and observed travel times, we also considered waveform matches between seismic records and synthetic seismograms. Figures 5 and 6 show the synthetic seismograms, ray paths and travel time fittings for two SPs.

Figure 7 represents the 2-D velocity model of the lithosphere obtained from the inversion. To show the velocity distribution clearly, besides velocity isolines (thin lines in the figure), the average velocity values in the lower crust and lithospheric mantle are also given with bold numbers in the model.

In general, from east to west, the average velocities of the lower crust and lithospheric mantle increase gradually. There is an abrupt change across the Taihang Mountain gravity gradient. This will be discussed in detail in the next section. Similarly, the C, M and LAB boundaries all deepen from east to west. However, the variation amplitudes and undulating shapes of these 3 boundaries are quite different. The variation and undulation amplitudes of the LAB are the greatest. Those of the Moho are second greatest and those of C boundary are the least. These results indicate that the main factors controlling tectonic deformation are from the deep Earth.

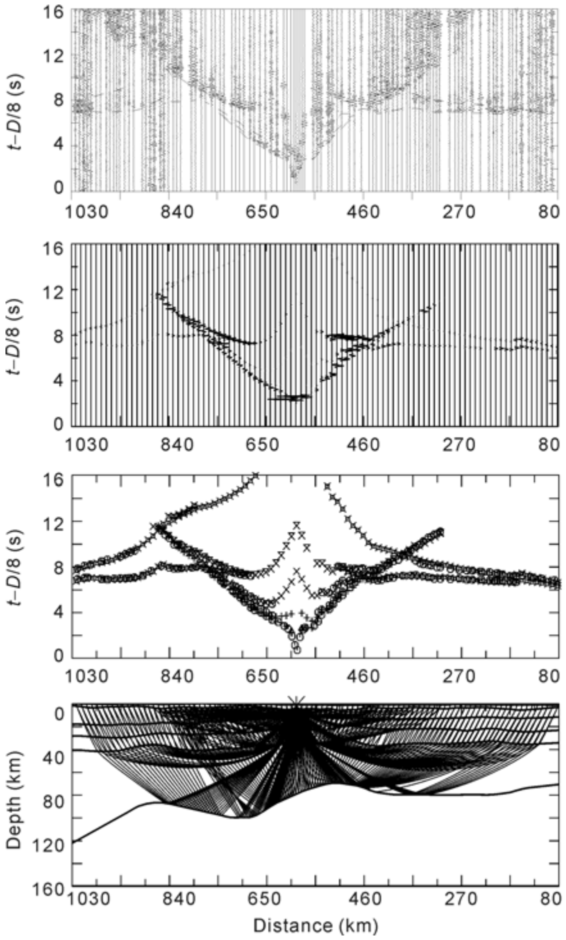

Figure 5 Theoretical seismogram, ray path and travel-time fitting for SP 592.

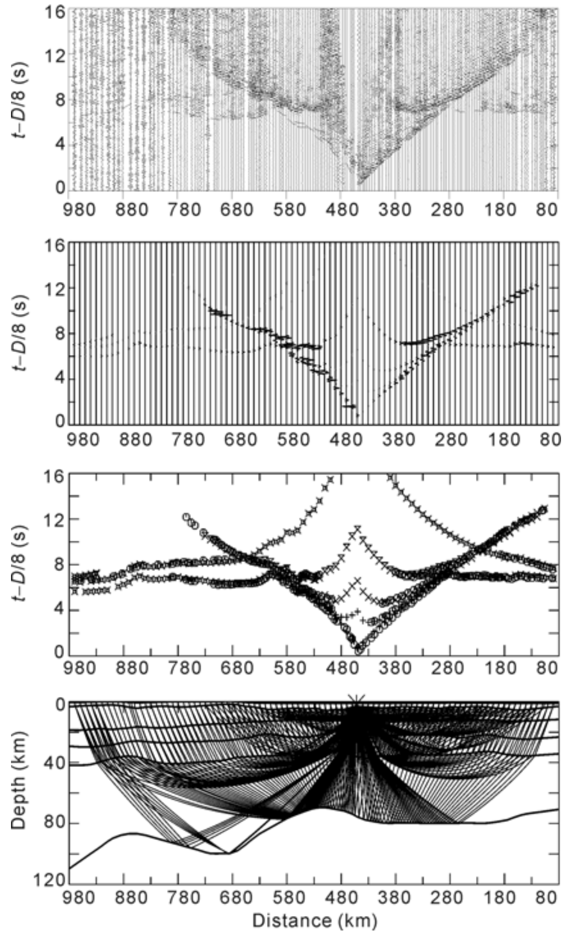

Figure 6 Theoretical seismogram, ray path and travel-time fitting for SP 451.

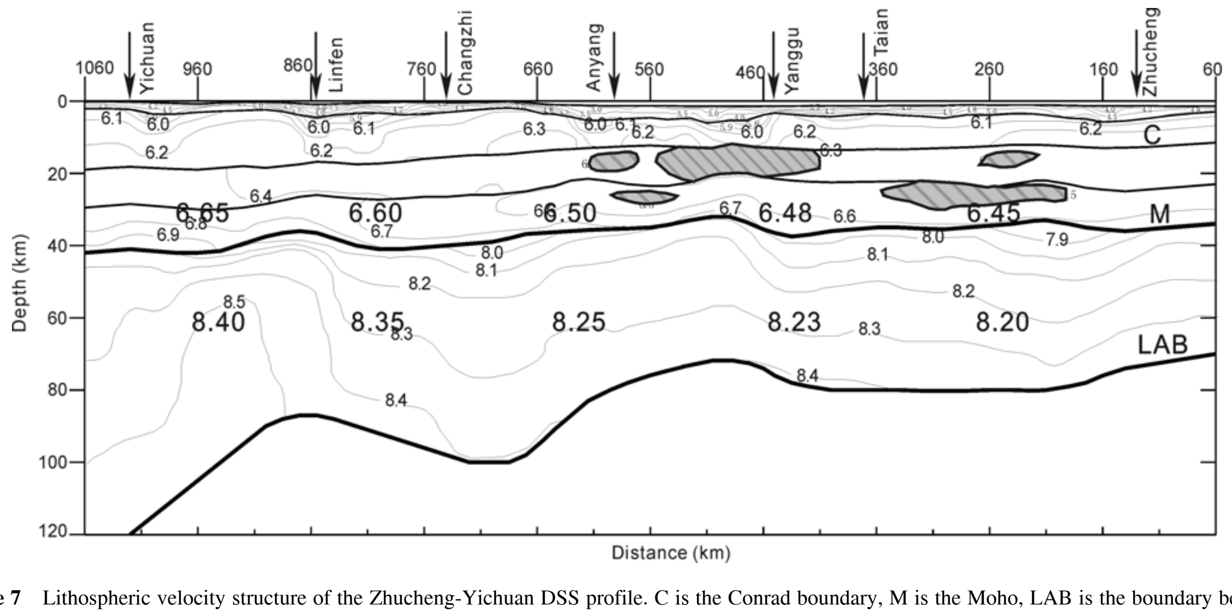

Figure 7 Lithospheric velocity structure of the Zhucheng-Yichuan DSS profile. C is the Conrad boundary, M is the Moho, LAB is the boundary between the lithosphere and asthenosphere, and the shadowed regions represent low velocity bodies in the crust.

4 Differences in lithospheric structures between two sides of Taihang Mountain

From Figure 7, it can be seen that there are great differences between two sides of Taihang Mountain. The differences are as follows.

(i) Lithospheric thickness. In the eastern region, the lithosphere is thinner with the thickness of about 70–80 km, while in the western region, the lithosphere is thicker with the thickness of 85–120 km. There is a jump of lithospheric thickness across the Taihang Mountain gravity anomaly belt, with a magnitude of about 30 km. Chen also discovered strong variations in lithospheric thickness in North China [10], which is about 80 km on average in the Bohai Bay basin, about 120 km beneath Taihang Mountain and about 90 km in the middle part of the NCC. From Gaomi to Jinan, the lithospheric thickness is 60–80 km [11]. Results from Xu and Zhao [12] using P wave travel time inversion also show a great difference in lithospheric thickness between two sides of Taihang Mountain. Similar results was also obtained from Magneto-telluric sounding (MTS) method. According to the inversion of the Yingxian-Shanghe MTS profile, there is a great horizontal variation in lithospheric thickness across the Taihang Mountain Front fault near Fuyang [2].

(ii) P wave velocity of the lithospheric mantle. In the eastern region, P wave velocities of the lithospheric mantle are lower, with a range of 7.9–8.4 km s^{-1} and an average of 8.20–8.23 km s^{-1}, while the velocities are higher in the western region, with a range of 8.1–8.55 km s^{-1} and an average of 8.35–8.40 km s^{-1}.

In comparison with previous DSS results from Pn inversion, Pn velocities from this experiment are slightly higher. In the past, most of the maximum receiving distances were less than 200 km. Thus, the ray paths of the observed Pn waves were very close to the Moho, and the results represented the velocities of the uppermost mantle. However, in this experiment the maximum observational distances are much greater than previous ones. Thus, Pn waves penetrate to a greater depth and the results reflect velocities in deeper parts of the upper mantle.

(iii) P wave velocity in the lower crust. In the eastern region, P wave velocities in the lower crust are lower, with a range of 6.3–6.7 km s^{-1}, and an average of 6.45–6.48 km s^{-1}, while the velocities are higher in the western region, with a range of 6.4–6.95 km s^{-1} and an average of 6.60–6.65 km s^{-1}.

(iv) Low velocity bodies in the crust. In the eastern region, there are low velocity bodies of various sizes in the middle and lower crust, while none are found in the western region.

Besides these four differences, considering the difference of the Pm waveform between two sides of Taihang Mountain, it can be deduced that the Moho in the eastern region is not a sharp discontinuity, but a complex transitional zone.

In the above analyses, we paid attention to deep, and not shallow layers. This is because velocities of the shallow layers are mainly affected by thicknesses of sediments and shallow structures. Velocities are lower beneath basins and depressions and higher beneath mountains and uplifts.

The lithospheric mantle is always the focus of the study on NCC. Many scientists have conducted extensive studies on the lithology and chemical composition in the lithospheric mantle of the NCC [2, 13, 14]. According to their results, the low velocity media beneath the eastern region correspond to spinel lherzolite and the lithospheric mantle belongs to weak depletion type, as shown in Figure 7. And the high velocity media beneath the western region correspond to harzburgite and the lithospheric mantle belongs to a strong depletion type. Generally speaking, the western lithospheric mantle is older, with an age of Late Archeozoic to Proterozoic; while the eastern lithospheric mantle is younger, and its most parts are modern, except for a small part, which is of Proterozoic age.

The above mentioned differences indicate that the Taihang Mountain gravity anomaly belt is also a belt with abrupt changes of lithospheric thickness and lithological composition. From Figure 7, it can be seen that although the crustal thicknesses of the two sides are different, the difference is not great. Thus, it is difficult to explain the existence of such a strong gravity gradient only using this difference. However, if the differences in lithospheric thicknesses and in lithospheric compositions are also taken into account, it is easier to understand the scale and variation amplitude of the Taihang Mountain gravity gradient.

Thus, it can be deduced that the lithosphere in the eastern region has been destroyed and transformed, including: 1) reduction of the total thickness of the lithosphere, and 2) changes of physical properties and composition of the rock. From Figure 7, it can be seen that the lithospheric thinning is mainly caused by thinning of the lithospheric mantle, while changes in physical properties and composition of the rock occurred not only in the lithospheric mantle, but also in the crust. Similar results were also obtained from seismic tomography using ambient seismic noise in North China. Rayleigh wave group velocity maps at periods of 7, 12 and 16 s show that there exist clear differences in group velocities between the two sides of Taihang Mountain. Group velocities in the eastern region are lower than those in the western region [15, 16].

As to the destruction mechanism of the eastern NCC, this problem remains unresolved. Until now, scientists have proposed various models for the destruction mechanism, including delamination, thermo-mechanical/chemical erosion, peridotite-melt reaction, mechanical extension and lithospheric weakening by hydration [17, 18]. By comparison, the first two models are more interested by scientists.

The above models are mainly based on studies of lithology and geochemistry. According to the results from this

DSS study, and also considering results from other geophysical methods, we tend to thermo-mechanical/chemical erosion model. Considering the position of the Zhucheng-Yichuan DSS profile, this opinion is only limited to the southern region of the NCC. The main reasons for this assertion are as follows:

(1) Structure and property of the crust-upper mantle boundary. The structure and property of the crust-upper mantle boundary reflect the type of interaction between crust and upper mantle experienced in this region. The differences in Pm waveforms between two sides of Taihang Mountain indicate that the Moho in the eastern region is not a sharp discontinuity, but a complex transitional zone with certain thickness. This means that underplating or thermal erosion may be the dominant factor. The bottom of the lithosphere becomes soft by heating action from the upwelling upper mantle. Then, under horizontal shearing action, the softened bottom is eroded gradually and changes into part of the asthenosphere, which is a rather slow process. The intrusion and heating action of the magma can extend upward further and affect the Moho. Thus, the Moho is also changed from a sharp discontinuity into a complex transitional zone with certain thickness. Conversely, delamination process completes in a short period. Some parts of the lithosphere are separated and drop into the asthenosphere by gravitational instability. Because of the delamination of the lower crust and lithosphere, some parts of the asthenosphere move upward to replace the volume formerly occupied, and thus a new sharp crust/upper mantle boundary is formed. The strong velocity contrast between the two sides of the boundary corresponds to a chemical boundary between low velocity felsic-mafic crustal substances and high velocity ultramafic upper mantle substances. The sharp crust/upper mantle boundary in the Yanshan district belongs to this type, and the destruction of the lithosphere is due to a delamination process [19]. Gao's geochemical study [20] on volcanic rocks at Xinglonggou, Yanshan, also supports this viewpoint.

(2) Existence of low velocity bodies. From Figure 7, it can be found that there are many low velocity bodies in the mid-lower crust in the eastern region, while none have been discovered in the western region. From another aspect, the exist of the crustal low velocity bodies provides an evidence for the intrusion of heat substances from the upper mantle. Because of this intrusion, the crustal substances were heated and low velocity bodies were formed.

Similarly, according to the 3-D S wave velocity model of the Capital Circle region from receiving function method, Liu et al. and Wang et al. also discovered crustal low velocity bodies in Tangshan, Sanhe and Yanhuai Basin, which are accompanied by uplifts of the crust-upper mantle boundary [21, 22]. They also asserted that formation of the low velocity bodies was probably related to intrusion during the destructive process of the NCC. Considering the geographical location, the region of their study is also located on the eastern side of Taihang Mountain and belongs to the eastern part of the NCC, although it is slightly further north.

(3) Geothermal heat flow and magmatism. According to Wang's study [23], geothermal heat flow and mantle heat flow of the eastern region are higher than in adjacent regions. In addition, widespread magmatism occurred in the eastern region of North China in the Cenozoic, while it seldom occurred in the western region [24].

The occurrences of the various differences between two sides of Taihang Mountain are inferred to be related to the motion of the heat substance in the asthenosphere. That is to say, the complicated crust-upper mantle transitional zone, crustal low velocity bodies, high heat flow values and widespread basaltic magmatism are all from a same source, the action of the heat substance from the upper mantle. It is this action that caused the thinning and destruction of the lithosphere.

5 Tectonic factors related to destruction of the lithosphere

There may be various tectonic factors related to the destruction of the NCC, such as the India-Eurasia block collision [25], South China-North China collision [26], plumes [27] and subduction of the Pacific Plate [28]. Until now, there has been no consistent answer to the question of which factor may be more reasonable or more important.

Based on analyses to geophysical results, Zhu and Zheng [29] suggested that Mesozoic subduction of the Pacific plate played an important role in the tectonic evolution of the NCC. Subduction would lead to fast and unstable flow in the upper mantle. This regional mantle flow system would result in an increase of melt/fluid content in the upper mantle of the NCC, which would promote softening of the continental lithosphere.

Huang and Zhao's results [30] from seismic tomography clearly reveal subduction of the Pacific Plate underneath the Eurasian Continent. In a vertical cross section along the EW direction, the subduction slab appears as a clear high velocity zone subducting westward. However, at a depth of 400 km, its subduction angle abruptly becomes small, and it continues to penetrate westward. Figure 8 is based on the model of Zhao et al. [31]. It shows that the front of the subducting slab has arrived inside of the NCC and near the Taihang Mountain gravity gradient. The authors believe that inside the wedge of the mantle, there is an asthenosphere flow eastward caused by the dragging effect of the subducting slab. This eastward flow inevitably transforms into strong upwelling because of the limitation and resistance of the subducting plate on the eastern side. The upwelling flow would soften the bottom of the lithosphere of the eastern region and produce thermal erosion, or cause continuous interaction between magma from the asthenosphere and the lithospheric mantle [32]. Furthermore, dehydration of the

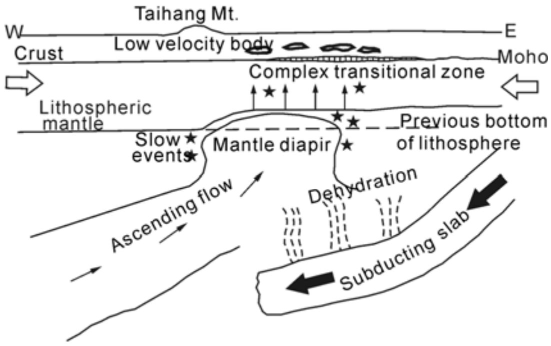

Figure 8 Schematic diagram showing the effect of the subducting Pacific slab on the NCC. After the model of Zhao et al. [31].

subducting slab can also affect the physical properties of the substances in the wedge. Thus, subduction of the Pacific plate is an important dynamical factor to change the properties of the lithospheric mantle of the NCC.

Considering the position of the subducting front, it is easy to understand the differences in lithospheric structures between two sides of Taihang Mountain. The effect of the subducting slab is mainly limited to the mantle wedge, while in the western region where the subducting slab does not reach, the effect is very small. The differences in lithospheric structures between two sides of Taihang Mountain, especially the strong thinning of the lithosphere in the eastern region, would lead to the great variation in gravity. Thus, it is easy to understand why the subducting front, the western boundary of the thinned lithosphere in North China and the Taihang Mountain gravity gradient are all so close to one another.

6 Conclusions

The 2-D velocity structures of the lithosphere from the Zhucheng-Yichuan DSS profile show that:

(1) There are great differences in lithospheric structures between two sides of Taihang Mountain. In the eastern region the lithosphere is thinner with the thickness of about 70–80 km, while in the western region it is thicker with the thickness of 85–120 km. There is a jump of the lithospheric thickness across the Taihang Mountain gravity anomaly belt, with a magnitude of about 30 km. P wave velocities of the lithospheric mantle and lower crust are lower in the eastern region and higher in the western region. In the eastern region, there are low velocity bodies in the middle and lower crust, while none are found in the western region.

Thus, the Taihang Mountain gravity anomaly belt is also a belt with abrupt changes in lithospheric thickness and lithological composition.

(2) There are great differences in Pm waveforms between two sides of Taihang Mountain. In the western region, Pm waves are clear, and possess large amplitudes and short durations; whereas in the eastern region, Pm waves are indistinct, and possess small amplitudes and long durations. It can be deduced that the Moho in the eastern region is not a sharp discontinuity, but a complex transitional zone.

Based on the above analyses, we suggest that geothermal mechanical-chemical erosion could be a main mechanism causing the thinning and destruction of the lithosphere beneath the eastern side of Taihang Mountain, and the subduction of the Pacific Plate is an important dynamical factor which changes the properties of the lithospheric mantle of the North China Craton.

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