Doi: 10.1007/s11589-009-0379-5

Integrated geophysical evidence for a new style of continent-continent collision beneath the western Kunlun in the northwestern China*

Rizheng He [1,2,✝] Rui Gao [1,2] Qiusheng Li [1,2] and Ye Guan [1,2]

[1] *Lithosphere Research Center, Institute of Geology, Chinese Academy of Geological Sciences, Beijing* 100037, *China*
[2] *Earthprobe and Geodynamics Open Laboratory, Chinese Academy of Geological Sciences, Beijing* 100037, *China*

Abstract Along the western Kunlun-Tarim-Tianshan geoscience transect in the northwestern China, an integrated geophysical investigation was carried out. Owing to the abominable natural conditions there, the sounding profile could not cross the whole transect, consequentially, a variety of velocity structures in the transverse and vertical orientations beneath the whole transect were not obtained, such as the case within the western Kunlun orogenic belt. To supply a gap of deep seismic soundings within the western Kunlun orogenic belt, we used the Bouguer gravity anomaly data and the relationship between the compressive wave and the density to obtain the density structure of the crust beneath the western Kunlun and the southern Tarim basin by a forward fitting of gravity anomalies within the two-dimensional polygonal model of uniform medium. The crust of the Tarim basin with a rigid basement was like an asymmetrical arc, whose surface feature was the Bachu uplift in the middle of the Tarim basin. Beneath the conjoint area between the Tarim basin and the western Kunlun belt, there was a V-shape structure located just up to the top of the uplifted Moho. The multi-seismological structures jointly revealed that the face-to-face continent-continent collision beneath the western Kunlun is a new structural style within the continent-continent collision zone, which is a real model proved by the numerical modeling.

Key words: **Western Kunlun; Tarim basin; integrated geophysical evidence; face-to-face continent-continent collision**
CLC number: P313.6 **Document code**: A

1 Introduction

The Western China is a perfect area to study the process of continent-continent collision between the Indian plate and the Eurasia plate. Here are the youngest large-scale orogen beyond the continent-continent collision and the Mesozoic-Cenozoic basin with the oldest craton basement developed in this area, and the deformation history of the Cenozoic continent is recorded by the particular kind of layout between the basin and the mountain. Many different models have been proposed to explain the evolution and uplift history of the Tibet in the Cenozoic era (Dewey and Burke, 1973; Tapponnier and Molnar, 1977; Tapponnier et al, 1982, 2001; Molnar and Tapponnier, 1978; Houseman et al, 1981; England and Houseman, 1986, 1989; Zhao and Morgan, 1987; Wu et al, 1991; Hamburger et al, 1992; Platt and England, 1994; Willett and Beaumount, 1994; Roger et al, 2000). Around the Tibetan plateau, the Western Kunlun mountains in the northwestern China is the key place to study and reveal the process of collision between the Indian and Asian plates. This region also holds an important clue to understanding the continental dynamics that might otherwise be inaccessible, especially when those orogenic belts have been quite active currently (Liu, 1999; Liu et al, 2000; Guo et al, 2002; Lou et al, 2007).

The continental dynamic environments of mutual compression within some intra-plate blocks developed beyond the collision between Tarim and the north margin of Tibetan plateau possibly happened (Lyon-Caen and Molnar, 1984; Gao et al, 1995). As a large-scale young intracontinental orogen in the Central

---

* **Received** 16 March 2009; **accepted in revised form** 9 June 2009; **published** 10 August 2009.

✝ **Corresponding author. e-mail**: herizheng@cags.ac.cn

Asia, Tianshan is far away from the collision boundary between the Indian and Asian plates, and the mechanics for its uplift has generally been argued for a long time. Some influential views on this question are about the effect of long-distance subduction from the Indian plate, which consider that Tianshan developed owing to the arc-continental collision in the Paleozoic (Windly, 1990; Gao, 1998), then re-uplifted and rebuilt as a result of the collision between the Inian and Asian plates in the Late Cenozoic (Burchfiel and Royden, 1991; Yin et al, 1998). Obviously, the re-uplift of Tianshan mountains in the Late Cenozoic involved the characteristics of the crust of Tarim, namely, whether or not the compressive stress resulted in the northward collision of the Indian plate could be transferred from the collision boundary to the interior of the Asian continent. Those frontal scientific questions about continental geodynamics brought about the deformation of intra-continental lithosphere, consequent arranges and deep process of Cenozoic uplift of some mountains in the center of Asia, which are involved in the collision of the two plates. They require further studies on the deep structure of lithosphere. To better understand the mutual actions between the northern Tibetan plateau and the Tarim basin, it is necessary to firstly study the deep structures beneath the junction of the western Kunlun mountains and the Tarim basin.

The across-line deep seismic soundings carried out in 1998 along the southern margin of Tarim basin (Zhang et al, 2002) and the deep seismic reflection profile parallel to the Southwest Tianshan conducted in 2004 (Yang et al, 2006) showed jointly that the western Kunlun mountains, the Tarim basin and the Southwest Tianshan have great differences in velocity structure. The velocity structure beneath the Tarim basin was similar to a typical stable block and that beneath the western Kunlun belts had the thickened crust of about 70 km depth and the slower velocity of lower crust (Zhang et al, 2002). Unfortunately, those works were only around the Tarim basin, but did not reach the western Kunlun mountains. Recently, the P-to-S converted teleseismic receiver functions have showed the southward subduction of the Asian lithosphere beneath the Indian lithosphere in a long distance beneath the east flank of west Himalayan syntax (Kumar et al, 2005) and on the western Kunlun mountains (Wittlinger et al, 2004; Xue et al, 2004), whose results were opposed to other evidences of gravity (Lyon-Caen and Molnar, 1984), relocated earthquakes (Chen and Yang, 2004) and seismic tomography (Xu et al, 1994, 2001; Zhou and Murphy, 2005; Huang and Zhao, 2006).

Moreover, the research on the geoscience transect along the Western Kunlun-Tarim-Tianshan, 1200-km long, in the northwestern China had been carried out during 1996 to 2000. The integrated geophysical investigation (deep seismic sounding, deep seismic reflection, broadband seismological observation, and interpretation of regional gravity & magnetic anomaly) were developed along this transect in order to reveal the state of lithosphere structure and its variations (Gao et al, 2000; Li et al, 2002; Lu et al, 2000; Xiao et al, 2001). On the other hand, as the surface topographic conditions limited some investigation work (such as deep seismic profile, deep seismic sounding) to be well carried out as shown in Figure 1, some existing gaps had obstructed us in well understanding the subsurface structures. In order to fill those gaps and to better understand the subsurface structures, modeling gravity data will be a good method to link them together. The profile from Quanshuigou to Aral shown in Figure 1, which is the southern part of the whole Tianshan-Tarim-Western Kunlun geoscience transect, is just a good link.

On the basis of the geoscience transect and the existing geophysical and geological evidences, this paper mainly introduces the tomography structure and the density structure and summarizes those results to better understand the entire lithosphere structure beneath the whole transect. Furthermore, we give a new structure style within the continent-continent collision zone, namely, the continent-continent collision with face-to-face style beneath the western Kunlun.

2 Tectonic settings and location of transect

As shown in Figure 1, the Tianshan-Tarim-Western Kunlun geoscience transect located in Xinjiang is about 1 200 km long from the north to the south, which begins from Doshanzi in the south margin of the Junggar basin, passes through the whole Tianshan mountains, crosses the Tarim basin, and ends at Quanshuigou in the Western Kunlun. The transect involves some tectonic units from the north to the south, such as the Junggar basin, North Tianshan terrane, Central Tianshan terrane, South Tianshan terrane, Tarim basin, Tieklic terrane, Western Kunlun terrane and Kara Kunlun terrane (Xiao et al, 2001). With sediment for the greater part, the Tarim basin which had a paleocontinental core and formed in

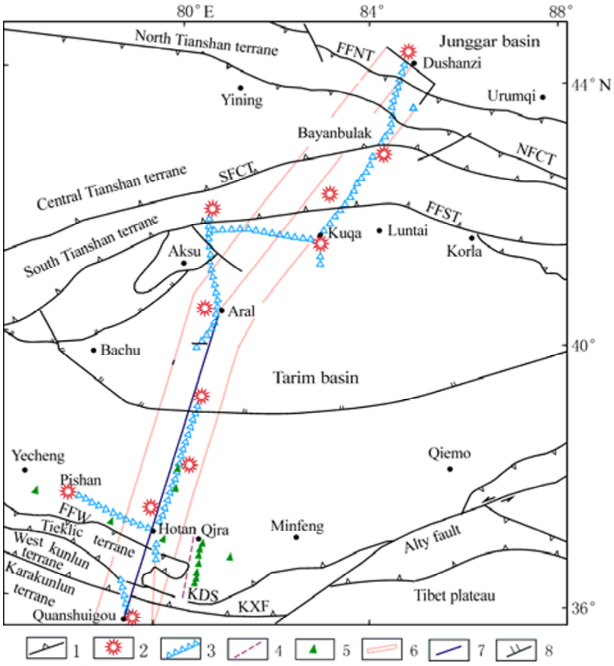

Figure 1 Location of Xinjiang geoscience transect and its tectonic division (Xiao, 2001; Yin, 2001). 1. Border fault of terrane; 2. Short point; 3. Deep seismic sounding station; 4. Deep seismic reflection profiles; 5. Broadband seismic observation station; 6. Xinjiang geoscience transect strip; 7. Location of profile from Quanshuigou to Aral in Figure 3B; 8. Thrust fault. FFNT: Fore-land fault of Northern Tianshan; NFCT: North Fault of Central Tianshan; SFCT: South Fault of Central Tianshan; FFST: Fore-land Fault of Southern Tianshan; FFW: Fore-land Fault of Western Kunlun; KDS: Kuda Suture

different eras and in different tectonic environments, is really a large complex basin and the earliest paleo-continent in the northwestern China (Xinjiang Bureau of Geology and Mineral Resource, 1993). There are some pre-Paleozoic and Paleozoic strata outcrops in the Tieklic terrane, which lies in the south of foreland fault of western Kunlun (FFW).

As a part of the main body of the Tibetan plateau, the Western Kunlun orogen that lies in the northwestern Tibetan plateau has strongly deformed, where earthquakes frequently happen. The Altyn fault zone, the abyssal shear fault zone in the Centeral Asia, ends off in the western Kunlun orogen (Yin, 2001). The southern boundary fault of Tarim block is a Kang Xiwa fault (KXF). Kara Kunlun block in the south of the KXF becomes a section of Yangzte-Qiangtang block in the Tibetan plateau (Xiao et al, 2001; Yin, 2001). Therefore, surveying the deep structures beneath the Western Kunlun belts is a key to understand the mechanism of the continent-continent collision and its far-away effects on the re-uplift of Tianshan orogenic belts in the Cenozoic era, which is the greatest orogen in the center of Asia (Molnar and Tapponnier, 1978; Yin et al, 1998).

3 Bouguer gravity anomaly around Xinjiang

The data around Xinjiang are derived from the Regional Gravity Anomaly Map of China (Scale 1:2 500 000) compiled by the Research Institute of Geophysical and Geochemical Exploration and the Technique Center of Regional Gravity Survey under the former Ministry of Geology and Mineral Resources. And the data around the adjacent area of Xinjiang are from the Map of Bouguer Gravity Anomaly in China and Adjacent Area (Scale 1: 1 000 000), which is mapped by Liu et al (1991). After the map was zoomed in the scale of 1:1 000 000, the Bouguer gravity anomaly map (Figure 2) was plotted according to a 10-km interval.

The Bouguer gravity anomaly within Altyn mountainous area extends northeastern-striking and has gentle changes. In the Tianshan Mountains, the gravity anomalies of South Tianshan and North Tianshan become a gradient-belt distribution, and that in Center Tianshan is lower than those in the other two sections. Generally, the features of gravity anomalies in Tianshan clearly differ from those in the two side basins, and Tianshan, in which the gravity anomalies are low and its contours are close, also differ from the features of the Altyn mountains and the western Kunlun mountains whose gravity anomalies distribute in gradient.

The gravity anomaly in the Tarim basin, which is relatively broad, becomes a U-shape distribution because the Tarim basin is surrounded by the Tianshan mountains, western Kunlun mountains and Altyn mountains. The gravity anomaly of Bachu uplift in the southwest of Tarim has the largest value (over -100×10^{-5} m/s^2.) in the whole Tarim basin. The Bouguer anomaly in the southwest of Bachu uplift is characterized by south-dipping slope, and Hotan depression is a relatively low value of gravity anomaly. In the north side of Bachu uplift, there is proximate east-westward concave gradient gravity between the Bachu uplift and the Keping uplift. In the East Tarim basin, the Bouguer anomaly changes gently. Its character shows that the crustal deformation in the East Tarim basin is not strong, mainly because of the influence of Altyn strike-slip fault on the Tarim basin.

However, the crust in the southwestern Tarim basin that becomes upward dome is affected under the strong compression from the Tibetan plateau and the Tianshan orogen. The gravity anomaly of the Kunlun orogen and the Altyn orogen is a steep south-dipping gradient belt, whose gravity value decrease from -300×10^{-5} m/s^2 to over -500×10^{-5} m/s^2, suggesting that the Moho boundary in the south margin of the Tarim basin has increasingly changed in depth into that of the Tibetan plateau (Lyon-Caen and Molnar, 1984).

As a whole, the contours of gravity anomaly vary with the characteristics of topography and physiognomy in this area. The contours in the north side of the map are characterized by a strip-shape north-westward extension, namely, the Altyn mountains. Those configurations of gravity anomaly within the Tarim basin become a U-shape. The gravity anomaly in the southwest side of Tarim basin, namely in the northwest margin of the Tibetan plateau, is characterized by steep southward dip and clear gradient belt.

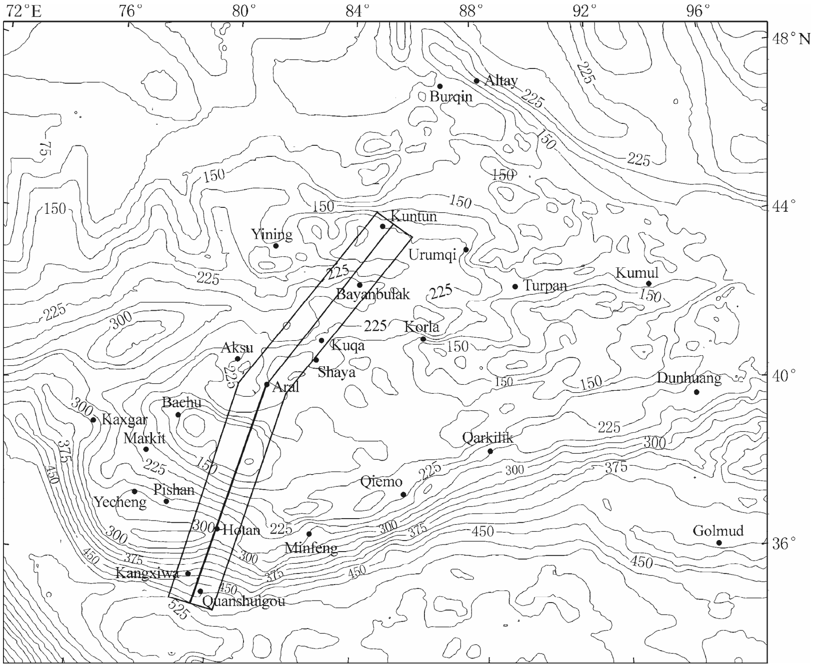

Figure 2 Map of filtered Bouguer gravity anomaly with contour interval of 25×10^{-5} m/s^2 in Xinjiang and adjacent area. The black solid line denotes the profile from Quanshuigou to Aral.

4 Density structure beneath the profile from Quanshuigou to Aral

As known, Bouguer gravity anomaly is mainly decided by the Moho, the difference in density between the crust and the mantle and the heterogeneity of the upper crust. Fortunately, in this study we have collected some limits from deep seismic soundings, deep seismic reflection and surface tectonics settings. To build an initial model of density structure beneath the whole transect, more geophysical and geological evidences need to be collected in this region as shown in Figure 1. In this study, the deep reflection profile provided a fine crustal structure beneath the western Kunlun (Gao et al, 2000). There is a group of north-dipping reflection phases, with a dip angle of about 35°, which can be continually traced beneath the western Kunlun mountains between 8–18 s (two travel time), but the reflection phase beneath the Tarim basin is south-dipping and the dip angle is about 27°. Between 18–19 s, a nearly horizontal reflection phase exists; between 19–30 s, the phase under the western Kunlun mountains is north-dipping with a high dip angle, yet it becomes south-dipping with a low dip angle, which is very similar to the receiver function image afterward (Kao et al, 2001). The location of DSS profile is shown in Figure 1. It is clear to identify the Pg phase from the crystalline basement, some phase from inner of crust and Pm phase from Moho. After phase inversion and forward fitting of ray tracing, the structure model of velocity (Lu et al, 2000; Li et al, 2002) could tell us some discontinuities within the crust and the upper mantle beneath the profile, such as the basement and the Moho, but certain geological structure information is not included, such as the dip and the depth of a fault within the crust beneath the profile.

The locations of some faults were limited by some surface geological traces. The depth that those faults extend downwards is decided step by step during the inversing and fitting processes. Moreover, some initial density values of each geological block within the model are decided by the modified empirical Nafe-Drake formula for the relationship between the density and the P-wave velocity, and the coefficients of Nafe-Drake formula were modified on the basis of some specific problems in China (Fen, 1986). To reduce the marginal effect of the model's sides in the forward-fitting process, the south end of the profile was extended southwards for about 100 km in length. In addition, the bottom depth of the model's space is given 100 km thick, and the velocity in the upper mantle is considered to be uniform, although many seismological evidences for the Tarim basin showed that the Tarim lithosphere had some heterogeneity (Xu et al, 1994, 2001; Liu et al, 2000; Huang et al, 2003; Kumar et al, 2005; Huang and Zhao, 2006). The gravity anomaly from the lithospheric mantle was too little to be noticed, which is not like that of the lithospheric mantle beneath the inner of the Tibetan plateau. In addition, the gravity data used in this study have low resolutions themselves.

Then, the gravity effect of each geological block can be calculated by the forward formula within the uniform media for the two-dimensional polygon model, and can be accumulated to obtain the forward-fitting gravity anomaly of the central profile. On the basis of the difference between the forward gravity anomaly and the filtered value, we modify the density value of each block in the model step by step, until the differences are minimum (Figure 3a) and the curve shape obtained is greatly accordant with the curve of the filtered Bouguer gravity anomaly. Finally, the density structure beneath the corridor has been obtained as shown in Figure 3b.

There is a clear feature within the Tarim block that the density in the uplift part (Marzhatager) near the center of the Tarim block is higher and thinner than that in its south-side depression, the Hotan depression with up to tens kilometers thick sediment that is similar to the result of petroleum profile (Jia, 1997). The density of the cover varies from 2.00 g/cm^3 on the surface to 2.60 g/cm^3 at the tope of the basement. The upper crust (10–15 km deep) has a great density range between 2.78 g/cm^3 and 2.84 g/cm^3. The density of the lower crust (about 35–45 km deep) of the Tarim basin varies between 2.95 g/cm^3 and 3.15 g/cm^3 and it's middle crust (25–35 km deep) have two layers. The top layer (25–35 km deep) is 2.84–2.88 g/cm^3 and the bottom is 2.89–2.96 g/cm^3.

Compared with the Tarim basin, the Kunlun belts are the most complicated geological tectonic zones, which locate in the northwestern margin of the Tibetan plateau (Figure 1). However, its structure of density is very simple in the vertical and has a very good feature of layer. The lower crust is 48–71 km deep with a density of 2.98 g/cm^3; the middle crust (25–48 km deep) has a density range between 2.91 g/cm^3 and 2.925 g/cm^3; the upper crust (0–18 km deep) can be divided into two layers and the density is less than 2.79 g/cm^3. The high conductor layer (Qin et al, 1994; Lu et al, 1995), 16–25 km deep, has a variable density range of 2.66–2.69 g/cm^3 as shown in Figure 3b. The V-shape, contra-positive triangular crustal block, which lies in the link zone between the Tarim basin and the Kunlun mountains, has two layers: the top layer (23–36 km deep) is 2.85 g/cm^3 and the bottom layer (36–45 km deep) is 2.88 g/cm^3. The result was similar to that of Layon-Caen and Molnar (1984). The fitting results have proved the occurrence of a deep collision between the Tarim block and the northward subducted India Plate on the lithosphere scale (He et al, 2006).

5 Structure beneath the west Kunlun mountains

Deep seismic reflection is an advantageous tool to directly obtain fine deep structures to understand continent-continent collision. The seismic reflection profile in the front of the western Kunlun mountains (Figure 3c) showed that the north-dipping reflection phase beneath the western Kunlun mountains cut off the south-dipping phase under the Tarim basin in the depth range between TWT 19 s and 30 s. Because such a structure is similar to a V-shape, the V-shape basin-and-range coupling relationship between the Tarim basin and the western Kunlun mountains (Gao et al, 2000) does exist. Compared with the reflection image in the southern Tibet obtained by INDEPTH-I (Zhao et al, 1993), the reflection phase in the western Kunlun mountains has a clear feature of high dip angle. These differences suggest that there are great differences in the geodynamic process of continent-continent collision around the Tibetan plateau. In the south side of the Tibetan plateau, it is easy to determine some reflection structures, such as the main Himalayan thrust (MHT) and the southern Tibetan detachments system (STDS), attributing to the northward-subducted Indian plate beneath the Tibetan plateau, because some clear surface geological faults can be easily traced from the surface downward to the deep. However, in the western Kunlun collision zone, the continuous intensive deformation happened together with the uplift of the Tibetan plateau in the Late Cenozoic (Yin, 2001).

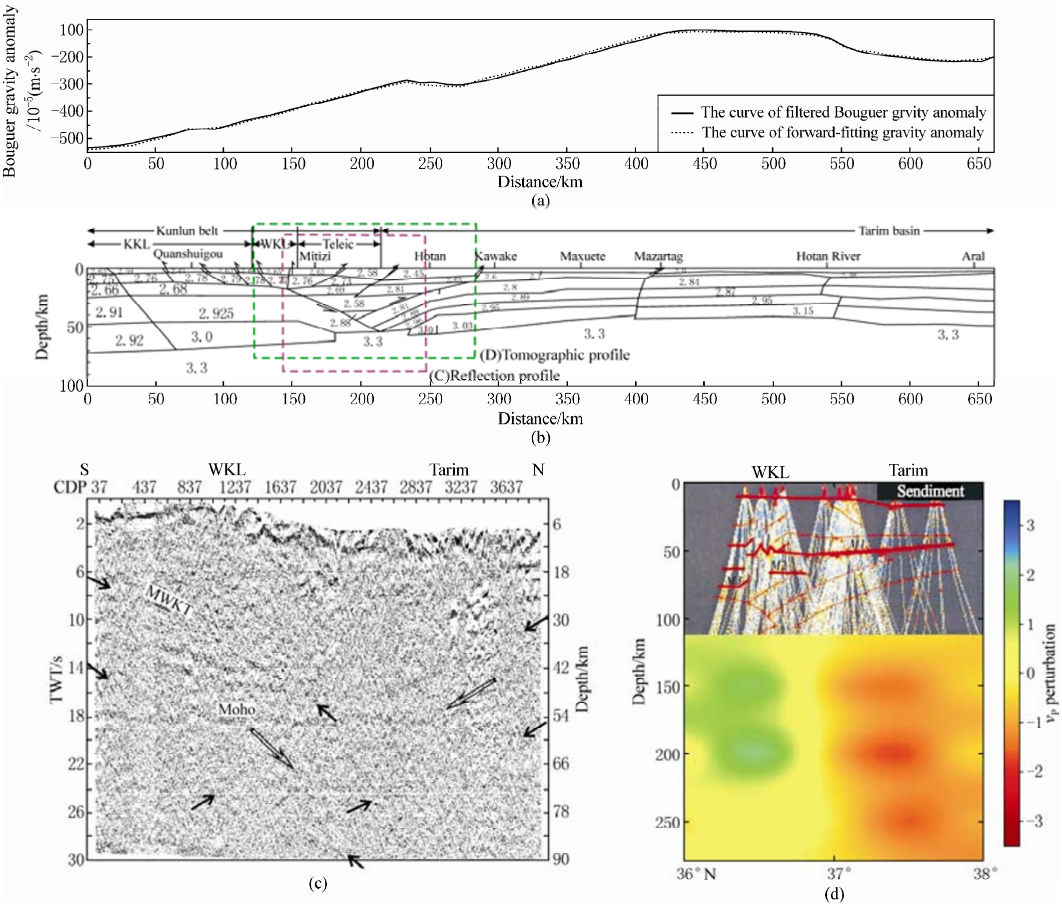

Figure 3 Geophysical structures beneath the profile from Quanshuigou to Aral. (a) Curves of comparison between the forward-fitting gravity anomaly and the observed anomaly; (b) Density structures (Density unit: g/cm^3) whose locations are shown in Figures 1 and 2; (c) Seismic reflection image (after Gao et al, 2000); (d) Velocity anomaly image from receiver function (the upper part; after Kao et al, 2000) and teleseismic P-wave tomographic image (the lower part; after He et al, 2006).

Although fine reflection structures had shown important evidences, the multi-seismological structure could strictly provide the limitation of subsurface structures, which is helpful to understand the complicated geodynamic process in this area. The broadband seismological observation is surely a good way to make it up.

Twelve three-component broadband stations with STS-2 sensors were arranged in the front of the western Kunlun mountains in Figure 1. Kao et al (2001) used the data set to calculate receiver functions to learn about the deformation within the whole lithosphere. He et al (2006) used the same data set to do teleseismic P-wave arrival-times tomography to obtain the velocity structure to trace the contact relation on the lithosphere scale. The upper part in Figure 3d from the receiver function image (Kao et al, 2001) suggests that: (1) there is a group of seismic phases like the topography uneven at the 15 km depth under the southern margin of the Tarim basin, which could be looked as crystalline basement because the feature also exists in the deep reflection image (Figure 3c); (2) A group of strong reflection phases, south-dipping, at the depth of 45 km beneath the southern margin of the Tarim basin, denotes the Moho under the Tarim basin, and the strong phases terminate at the north-dipping reflection phase beneath western Kunlun mountains, which is the same as the result by deep seismic soundings (Li et al, 2002) and reflection image (Gao et al, 2000); (3) There is a strong north-dipping phase at about 45-km depth under the Kunlun mountains, which inserts into 140 km deep under the Tarim basin. The lower part in Figure 3d is a tomographic image (He et al, 2006), which shows that there are high velocity anomalous body and low velocity anomaly at the depth of 100 km to 250 km along 80°E within the lithosphere mantle. The high velocity anomalous body just locates under the western Kunlun mountains, and what lies beneath the Tarim block is the low velocity anomaly.

Obviously, such clear structures from the surface to the lithosphere mantle are constructed together by receiver function (Kao et al, 2001) and teleseismic tomography (He et al, 2006), which are validated by the gravity fitting model as shown in Figure 3b and they are also in accord with the deep seismic reflection image (Figure 3c; Gao et al, 2000).

6 Discussion and conclusions

In the broadband seismological images (Figure 3d), the low velocity anomaly in the north side obviously represents the lithospheric mantle of the Tarim block, as one part of the Eurasia plate, namely the low velocity anomaly is the south end of the Eurasian plate. However, as the western Kunlun mountain is no more than 500 km away from the Indian plate and the distance here is the shortest in the Tibetan plateau, and as it is also the eastern flank of the west syntax of the Tibetan plateau, whether the high velocity anomaly does denote the frontier of the northward-subducted Indian plate or not still remains in dispute (Pan, 1990; Matte et al, 1996; Maheo et al, 2002; Cowgill et al, 2003). Recently, many geophysical evidences have been shown to interpret it as the frontier of the northward-subducted Indian plate.

Chen and Yang (2004) collected earthquake events, whose foci depth is no less than 90 km and m_b is no less than 4.6, happened within the area during 1963 and 1999 to study the foci. The result suggested that the foci depth became deeper and deeper from 32°N to 38°N. In the comparison of these foci with those in the southern Tibetan plateau, the great contrast revealed that the foci beneath the western Kunlun mountains should be attributed to the strong lithospheric mantle of the northward-subducted Indian plate beneath the Tibetan plate collided with the lithospheric mantle of the Eurasian plate beneath the western Kunlun mountains (Chen and Yang, 2004). Moreover, our tomographic image (Figure 3d), together with the large-scale tomographic images (Xu et al, 2001; Zhou and Murphy, 2005; Huang and Zhao, 2006) have provided a direct evidence for the speculation (Chen and Yang, 2004) and the northward-subducted Indian plate has not broken off since the 25 Ma (Maheo et al, 2002). Although the western Kunlun collision zone included different terranes formed in different eras as shown in Figure 1 (Pan, 1990; Bi et al, 1999; Xiao et al, 2001), the continent-continent collision with the Eurasian plate on the lithosphere scale happened at present is the lithospheric mantle of the northward-subducted Indian plate, not the northward-subducted Qiangtang terrane (Cowgill et al, 2003). Moreover, the sounding results from integrated seismic techniques (Figures 3c and 3d) suggest that there is a V-shape basin-and-ranges coupling relationship between the Tarim basin and the western Kunlun Mountains on the crust scale, which is not agreeable to that the Tarim block subducted southward beneath the western Kunlun mountains under the Tibetan plateau in a long distance (Lyon-Caen and Molnar, 1984; Matte et al, 1996).

In the present day under the western Kunlun mountains, as the northwestern margin of the whole Tibetan plateau, the V-shape convergence within the crust implicated by the deep seismic reflection image (Gao et al, 2000) as shown in Figures 3b and 3d, and the nearly horizontal south-to-north bidirectional collision between the Indian and the Eurasian plates on the lithosphere scale (Xu et al, 1994, 2001; Zhou and Murphy, 2005; He et al, 2006; Huang and Zhao, 2006) is a new structure style in the continental geodynamics, namely the face-to-face continent-continent collision, which is obviously different from the structure style in the southern margin of the Tibetan plateau (Zhao et al, 1993). Pysklywec (2001) used the numerical models of the crust-mantle system to consider the case of a simplified continent-continent plate collision, and furthermore gave a modeling image of continent-continent collision, which is very similar to the V-shape structure beneath the western Kunlun mountains. And on the basis of the modeling result, the style of post-collision subduction is largely controlled by the strength of the mantle lithosphere (Pysklywec, 2001). The above-mentioned investigations of deformation styles beneath the western Kunlun belts have led to a real geodynamic model indicating a certain feature of deformation during continental collision.

The conclusions in this paper are as follows:

(1) The density structure by fitting gravity anomaly with deep seismic sounding profile has better limit structures in the southern parts of the geoscience transect and has shown further tectonic information, such as the depth and dip of some important faults in the area.

(2) The integrated geophysical evidences from deep seismic reflection, teleseismic tomography, receiver function and density gravity have all together provided strict limitation of crustal and lithospheric structures beneath the western Kunlun mountains to better understand the complicated tectonic units.

(3) On the basis of the integrated geophysical evidences, a new structure style of continent-continent collision between the Indian and the Eurasian plates is proposed that the face-to-face continent-continent collision have two parts: one is the V-shape convergence within the crust, and the other is the nearly horizontal south-to-north bidirectional collision on the lithosphere scale, which have been proved by the numerical models (Pysklywec, 2001).

Acknowledgements This work is financially supported by the National Natural Science Foundation of China (40404011, 40774051, 49734230), the basic outlay of scientific research work from Ministry of Science and Technology of the People's Republic of China in 2007 and 2008 (J0707, J0803), Sino-American collaboration project from Ministry of Science and Technology of the People's Republic of China (2006DFA21340), China National Probing Project (SinoProbe-02), and Open Fund of Geo-detection Laboratory, Ministry of Education of China, and China University of Geosciences (No. GDL0602). We would like to express our thanks to Academician Xuchang Xiao and Prof. Xun Liu of the Chinese Academy of Sciences for their valuable directions in discussion with us about geological problems.

References

Argand E (1924). La tectonique de l' Asie. In: *Proc* 13*th* *Int Geol Cong,* 7, 171–172.

Bi B, Wang Z G, Wang Y L and Zhu X Q (1999). History of tectono-magmatic evolution in the Western Kunlun Orogen. *Science in China* (*Series D*) **29**(5): 398–406 (in Chinese with English abstract).

Burchfiel B C and Royden L H (1991). Tectonics of Asia 50 years after the death of Emile Argand *Eclogae Geol Helv* **84**: 599–629.

Chen W P and Yang Z H (2004). Earthquakes beneath the Himalayas and Tibet: Evidence for strong lithospheric mantle. *Science* **304**: 1 949–1 952.

Cowgill E, Yin A, Harrison T M and Wang X F (2003). Reconstruction of the Altyn Tagh fault based on U-Pb geochronology: Role of back thrusts, mantle sutures, and heterogeneous crustal strength in forming the Tibetan Plateau. *J Geophys Res* **108**(B7): 2 346, doi: 10.1029/2002JB002080.

Dewey J F and Burke K (1973). Tibetan variscan and Precambrian basement reactivation: Products of continental collision. *J Geol* **81**: 683–692.

England P and Houseman G (1986). Finite strain calculations of continental deformation: 2. Comparison with the India-Asia collision zone. *J Geophys Res* **91**: 3 664–3 674.

England P and Houseman G (1989). Extension during continental convergence, with application to the Tibetan Plateau. *J Geophys Res* **94**(B12): 17 561–17 579.

Fen R, Yan H F and Zhang R S (1986). A fast inverse method of three-dimensional potential field and its program design. *J Geology* **4**: 390–402 (in Chinese with English abstract).

Gao J, Li M S, Xiao X C, Tang Y Q, He G Q (1998). Paleozoic tectonic evolution of the Tianshan Orogen, northwestern China. *Tectonophysics* **287**: 213–231.

Gao R, Cheng X Z and Ding Q (1995). Preliminary geodynamic model of Golmud-Ejinqi geoscience transect. *Acta Geophysica Sinica* 38(Suppl): 3–14 (in Chinese with English abstract).

Gao R, Huang D D, Lu D Y, Qiang G, Li Y, Kuang C Y, Li P W, Feng R and Guan Y (2000). A deep seismic reflection profile across the conjunction zone between West Kunlun Mountains and Tarim Basin. *Chinese Science Bulletin* **45**(24): 2 281–2 286.

Guo B, Liu Q Y, Chen J H and Li S C (2002). Relocation of earthquake sequences using joint hypocenter determination method: Portable seismic array study in Jiashi Region, Xinjiang. *Seismology and Geology* **24**(2): 199–207 (in Chinese with English abstract).

Hamburger M W, Sarewitz D R, Pavlis T L and Popandopulo G A (1992). Structural and seismic evidence for intracontinental subduction in the Peter the First Range, Central Asia. *Geol Soc Am Bull* **104**: 397– 408.

He R Z, Zhao D P, Gao R, Wang B S, Qi C(2006). Teleseismic P-wave tomography of lithospheric mantle beneath western Kunlun orogenic belts. *Chinese J Geophys* **49**: 778–787 (in Chinese with English abstract).

Houseman G A, McKenzie D P and Molnar P (1981). Convective instablility of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. *J Geophys Res* **86**: 6 115–6 132.

Huang J L and Zhao D P (2006). High-resolution mantle tomography of China and surrounding regions. *J Geophys Res* **111**(B9): B09305, 10.1029/2005JB004066.

Huang Z, Su W, Peng Y, Zheng Y and Li H (2003). Rayleigh wave tomography of China and adjacent regions. *J Geophys Res* **108**(B2), doi: 10.1029/2001JB001696.

Jia C Z (1997). *Tectonic Characteristics and Petroleum*: *Tarim Basin*, *China*. Petroleum Industry Press, Beijing, 1-202.

Kao Honn, Rui Gao, Ruey-Juin Rau, Shi D N, Chen R-Y, Guan Y and Wu F T (2001). Seismic image of the Tarim basin and its collision with Tibet. *Geology* **29**(7): 575–578.

Kumar P, Yuan X, Kind R and Kosarev G (2005). The lithosphere–asthenosphere boundary in the Tien Shan-Karakoram region from S receiver functions: evidence for continental subduction. *Geophys Res Lett* **32**: L07305. doi:10.1029/2004GL022291.

Li Q S, Gao R, Lu D Y, Li J W, Fan J Y, Zhang Z Y, Liu W, Li Y K, Yan Q R, Li D X and Wide angle team (2002). Tarim underthrust beneath western Kunlun: Evidence from wide-angle seismic sounding. *Journal of Asian Earth Sci* **20**: 247–253.

Liu G D (1991). the Map of Bouguer Gravity Anomaly in China and Adjacent Area (Scale 1: 1 000 000). Geological Publishing House, Beijing (in Chinese).

Liu Q H (1999). Study on mid-depth earthquakes beneath Hindu Kush-Pamirs region. *Acta Seismologica Sinica* **21**(3): 233–240 (in Chinese with English abstract).

Liu Q Y, Chen J H, Li S C and Guo B (2000). Passive seismic experiment in Jiashi, Xinjiang strong earthquake region and discussion on its seismic genesis. *Chinese J Geophys* **43**(3): 356–365 (in Chinese with English abstract).

Lou X T, Diao G L, Ye G Y and Ning J Y (2007). Spatial distribution of intermediate earthquakes and focal mechanism solutions in the Pamir-Hindu Kush region. *Chinese J Geophys* **50**(5): 1 448–1 455 (in Chinese with English abstract).

Lu D Y, Li Q S, Gao R,Li Y K, Li D X, Liu W and Zhang Z Y(2000). A deep seismic sounding profile across the Tianshan Mountains. *Chinese Science Bulletin* **22**: 2 100–2 106 (in Chinese with English abstract).

Lu X B, Shi Y and Tian C L (1995). Tectonic electrical characteristics and a model subducting patterns of southwestern Tarim basin-west Kunlun area. *Experimental Petroleum Geology* **17**(3): 238–248 (in Chinese with English abstract).

Lyon-Caen H and Molnar P (1984). Gravity anomalies and the structure of western Tibet and the southern Tarim basin. *Geophys Res Lett* **11**: 1 251–1 254.

Maheo G, Guillot S. Blichert-Toft J, Rolland Y and Pecher A (2002). A slab breakoff model for the Neogene thermal evolution of South Karakorum and South Tibet. *Earth and Planetary Science Letters* **195**: 45–58.

Matte P, Tapponnier P, Arnaud N, Boujot L, Avouac J P, Vidal P, Liu Q, Pan Y and Wang Y (1996). Tectonics of Western Tibet, between the Tarim and the Indus. *Earth Planet Sci Lett* **142**: 311–330.

Molnar P and Tapponnier P (1978). Active tectonics of Tibet. *J Geophys Res* **85**: 5 361–5 375.

Pan Y S (1990). Tectonic features and evolution of the Western Kunlun Mountain region. *Scientia Geologica Sinica* (3): 224–232 (in Chinese with English abstract).

Platt J P and England P (1994). Convective removal of lithosphere beneath mountain belts: thermal and mechanical consequences. *Am J Sci* **294**: 307–336.

Pysklywec R N (2001). Evolution of subducting mantle lithosphere at a continental plate boundary. *Geophys Res Lett* **28**: 4 399–4 402.

Qin G Q, Chen J H, Liu D J, Gu Q, Xiong Y W and Li H X (1994). The characteristics of the electrical structure of the crust and upper mantle in the region of the Kunlun and the Karakorum Mountains. *Acta Geophysica Sinica* **37**(2): 193–199 (in Chinese with English abstract).

Roger F, Tapponnier P and Arnaud N (2000). An Eocene magmatic belt across central Tibet: mantle subduction triggered by the Indian collision? *Terra Nova* **12**: 102–108.

Tapponnier P and Molnar P (1977). Active faulting and tectonics of China. *J Geophys Res* **82**: 2 905–2 930.

Tapponnier P, Peltzer G, LeDain A Y, Armijo R and Cobbold P (1982). Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology* **10**: 611–616.

Tapponnier P, Xu Z, Roger F, Meyer B, Arnaud N, Wittlinger G and Yang J (2001). Oblique stepwise rise and growth of the Tibet Plateau. *Science* **294**: 1 671–1 677.

Willett S D and Beaumont C (1994). Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision. *Nature* **369**: 642–645.

Windley B F, Alen M B, Zhang C, Zhao Z Y and Wang G R(1990). Paleozoic accretion and Cenozoic redeformation of the Chinese Tianshan range, central Asia. *Geology* **18**: 128–131.

Wittlinger G, Vergne J, Tapponnier P, Farra V, Poupinet G, Jiang M, Su H P, Herquel G and Paul A (2004). Teleseismic imaging of subducting lithosphere and Moho offsets beneath western Tibet. *Earth Planet Sci Lett* **221**: 117–130.

Wu G J, Gao R, Yu Q, Chen Q Y, Meng L S, Dong X B, Cuui Z Z, Yin Z X, Shen X J and Zhou Y X (1991). Integrated investigations of the Qinghai-Tibet plateau along the Yadong Golmud geoscience transect. *Acta Geophysica Sinica* **34**: 552–562 (in Chinese with English abstract).

Xiao X C, Liu X, Gao R, Kao H and Luo Z H (2001). Collision tectonics between the Tarim block (Basin) and the northwestern Tibet Plateau: new observations from a multidisciplinary geoscientific investigation in the western Kunlun Moutains. *Acta Geologica Sinica* (English edition) **75**(2): 126–132.

Xinjiang Bureau of Geology and Mineral Resource (1993). *Regional Geology of Xinjiang Uygur Autonomous Region*. Geological Publishing House, Beijing,1-260 (in Chinese with English abstract).

Xu Y, Liu F T, Liu J H, Chen H and Sun R M (2001). Deep features of continental collision belts in northwestern China and their dynamic implications. *Chinese J Geophys* **44**(1): 40–47 (in Chinese with English abstract).

Xu Y, Zhu J S, Liu Z J, Zhang H Q and Zhu Y (1994). 3-D velocity imaging of crustal and upper mantle beneath Xinjiang Tianshan and its adjacent region. *Acta Seismologica Sinica* **16**(4): 480–487 (in Chinese with English abstract).

Xue G Q, Jiang M, Su H P, Qian H, Wang Y X, Dong Y J, Wittligner G. and Poupinet G. (2004). Study on the deep structure beneath Yecheng-Shiquanhe area in Tibet plateau by tomography. *Science in China* (*Series D*) **34**(4): 329–334 (in Chinese with English abstract).

Yang Z X, Zhang X K, Jia S X, Liu B J, Feng S Y, Zhao C B, and Pan J S (2006). Fine crustal structure in the Jiashi earthquake swarm region revealed by deep seismic reflection profiling. *Chinese J Geophys* **49**(6): 1 701–1 708 (in Chinese with English abstract).

Yin A (2001). Geological evolution of orogen in Himalaya-Tibet Plateau. *J Geology* **22**(3): 193–230 (in Chinese with English abstract).

Yin A, Nie S, Craig P, Harrison T M, Ryerson F J, Qian X and Yang G. (1998). Late Cenozoic tectonic evolution of the southern Chinese Tian Shan. *Tectonics* **17**(1): 1–27.

Zhang X K, Zhao J R, Zhang C K, Ren Q F, Nie W Y, Cheng S X, Pan S Z and Tang Z Q (2002). Crustal structure at the northeast side of the Pamir. *Chinese J Geophys* **45**(5): 665–671 (in Chinese with English abstract).

Zhao W L and Morgan J W (1987). Injection of the Indian lower crust into Tibetan lower crust: A two-dimensional finite element model study. *Tectonics* **6**: 489–504.

Zhao W, Nelson K D and Project INDEPTH Team (1993). Deep seismic reflection evidence for continental underthrusting beneath southern Tibet. *Nature* **366**: 557–559.

Zhou H and Murphy M A (2005). Tomographic evidence for wholescale underthrusting of India beneath the entire Tibetan plateau. *Journal of Asian Earth Sci* **25**: 445– 457.