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Investigation of plateau basin crustal structures and thickening mechanisms in the northeastern margin of the Tibetan plateau*

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Abstract This paper uses deep seismic sounding (DSS) data to contrast and analyze the crustal structures of three plateau basins (Songpan-Garze, Qaidam, Longzhong) in the northeastern margin of the Qinghai-Xizang (Tibetan) plateau, as well as two stable cratonic basins (Ordos, Sichuan) in its peripheral areas. Plateau basin crustal structures, lithological variations and crustal thickening mechanisms were investigated. The results show that, compared to the peripheral stable cratonic basins, the crystalline crusts of plateau basins in the northeastern margin are up to 10–15 km thicker, and the relative medium velocity difference is about 5% less. The medium velocity change in crustal layers of plateau basin indicates that the upper crust undergoes brittle deformation, whereas the lower crust deforms plastically with low velocity. The middle crust shows a brittle-to-plastic transition zone in this region. Thickening in the lower crust (about 5–10 km), and rheological characteristics that show low-medium velocity (relatively reduced by 7%), suggest that crustal thickening mainly takes place in lower crust in the northeastern margin of the Tibetan plateau. The crust along the northeastern margin shows evidence of wholesale block movement, and crustal shortening and thickening seem to be the main deformation features of this region. The GPS data show that the block motion modes and crustal thickening in the Tibetan plateau is closely related to the peripheral tectonic stress field and motion direction of the Indian plate. The Mani-Yushu-Xianshuihe fold belt along the boundary between the Qiangtang block and the Bayan Har block divides the different plateau thickening tectonic environments into the middle-western plateau, the northeastern margin and the southeastern plateau.

Key words: **northeastern margin of the Tibetan plateau; plateau basin; stable cratonic basin; deep seismic sounding; thickening mechanism**

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1 Introduction

The Qinghai-Xizang (Tibetan) plateau is key to our understanding of plate tectonics, especially continental plate evolution and convergence. Since the Cenozoic, the continuous collision between the Indian and Eurasian plates has created the modern Tibetan plateau, and has involved the convergent Qaidam, Bayan Har, Qiangtang, and Lhasa blocks in the great geological reconstruction of this region (Enkin et al., 1992).

It has long attracted many of the world's earth scientists to study the tectonic evolution and crustal thickening mechanisms of the "roof of the world", where the elevation ranges from 3 500 m to 8 800 m (with an average of about 4 500 m), and the crustal thickness is 50–80 km (the average is about 65 km) (Lu et al., 2006). In the 1920's, Argand (1924) assumed that Indian mainland is being driven beneath the Asian continent, leading to the uplift of the Tibetan plateau and thereby forming a "double layer crust." Willett and Beaumont (1994) put forward the continent-continent collision model of Asian lithospheric mantle subduction beneath the Tibetan plateau. Matte et al. (1996) and Yin and Harrison (2000) put forward the "high-angle diving" model and "low-angle diving" model, respectively, while

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Tapponnier et al. (2001) proposed the "multiple stage diving" model. Clark and Royden (2000) and Royden et al. (2008) introduced the idea of "lower crustal flow" in their study on the uplift of the Tibetan plateau and the coupling between the plateau and the peripheral stable blocks to discuss the tectonic linkage between viscous material flowing in deep crustal levels, plateau crustal thickening, and the uplift of margin orogenic belts. From the end of 1950's until today, geophysical explorations, especially deep seismic sounding as a main technology, were gradually developed. The Tibetan plateau lithospheric structure, the overall plateau uplift tectonic dynamics, continental margin collision process, as well as the interactions among the plateau interior blocks were explored, and many achievements were made. The plateau crustal thickness has been inferred, which have revealed a multilayer structure with local melting in the crust (Zeng and Gan, 1961; Teng, 1979; Teng et al., 2013; Zhao et al., 1993; Cui et al., 1995; Nelson et al., 1996; Zhang et al., 2011). Zhao et al. (2010) used teleseismic receiver function inversion to infer that there are more complicated Indian-Asian plate collision boundaries beneath the Tibetan plateau, and they identified the structural block boundaries within different regions in the plateau's interior. The present GPS data confirm that the motion modes of the active blocks within the plateau are different, and that their movement directions and velocities are not all the same (Zhang et al., 2002). It is the variations in these block movement directions and velocities, the differences in adjusting and accommodating to the tectonic stress field in different block boundaries and their interiors, as well as the crustal thickness difference (∼40 km) between western Kunlun syntaxis (∼90 km, Wittlinger et al., 2004) and the eastern Zoige basin (∼50 km, Jia et al., 2010), that have caused the deformation mechanisms and crustal uplift structures in the Tibetan plateau to be more complicated that previously envisioned.

Due to the remote natural environment of the Tibetan plateau, especially in its central and western areas with high altitude, it is very difficult to collect geophysical data in this region. Today, the investigation for deep structures is mainly through teleseismic receiver function to infer largescale structural features beneath the plateau. Because the fieldwork conditions and observation methods are not ideal, it is difficult to use active source seismic methods to explore the detailed crustal structures and lithologic variation with the depth in the vast central and western plateaus. These problems mean that there are many difficulties in understanding the different models that have been proposed concerning plateau uplift and thickening mechanisms.

So, we aim to explore the crustal lithologic diversity within the plateau blocks, the lithologic variations with depth as well as the thickening processes. In recent years, several preliminary seismic profiles were completed with new portable digital seismic instruments in the northeastern part of the Tibetan plateau and its peripheral area (Figure 1). In this paper, these DSS data are used to contrast and study the seismic phase features in the different blocks of the northeastern plateau margin and the basins within the stable massif of the plateau periphery. We study the implications of these data on the detailed crustal structures, and probe into the seismic evidence of crustal tectonic deformation and uplift as well as the geodynamic processes that have occurred in this region.

2 Tectonic setting and DSS

The northeastern Tibetan plateau is an important place where the Indian-Eurasian plate motion direction changes from nearly north-south to northeast, therefore creating convergence along the plate margins to the east-west. As a result of peripheral obstructions of the eastern Yangtze block, the northeastern North China and Alxa blocks, as well as the extrusion deformation of the Qaidam and Bayan Har blocks in the northeastern margin interiors, the above tectonic blocks formed as core and margin orogenic belts with different trends along the northeastern margin of the convergent zone. These fold belts include the Longmenshan fold system in the southeastern region, the Qilianshan fold system at northern margin, the Liupanshan in the northeastern edge, and the east Kunlun-Qinling fold system in the northeastern margin of the Tibetan plateau. Tectonic structures trending east-west and north-south meet in this region, making it one of the most tectonically active areas on the Tibetan plateau (Figure 1).

Since the northeastern Tibetan plateau has relatively low altitude, and the seismic instruments for DSS investigation have been greatly improved in China, it is possible for us to carry out DSS explorations in uninhabited regions of the plateau. In the last ten years,

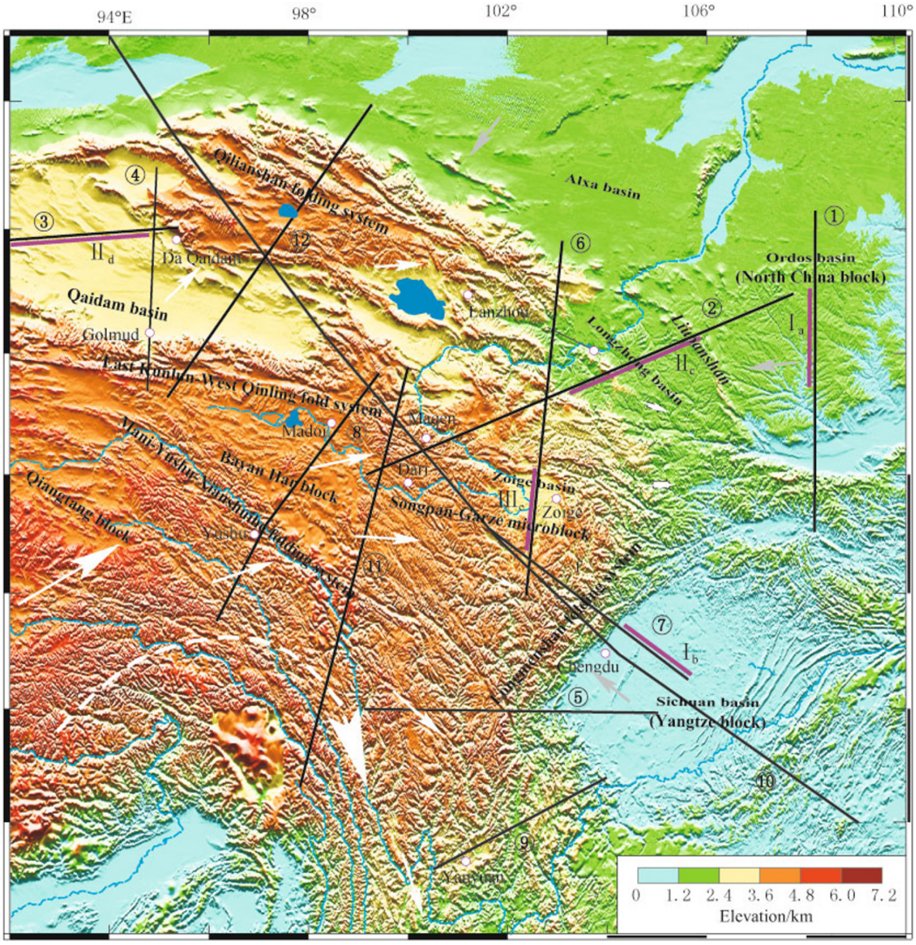

Figure 1 Simplified map of terrain, tectonic division, block movement and DSS profiles in the northeastern margin of the Tibetan plateau and its peripheal area. DSS profiles (black lines) are ① Xi'an-Baotou (1987), ② Dari-Lanzhou-Jingbian (1999), ③ Da Qaidam-Ruoqiang (2000), ④ Golmud-Da Qaidam-Huahaizi (2000), ⑤ Zizhong-Batang, ⑥ Barkam-Hezuo-Gulang (2005), ⑦ Suining-Aba (2010), ⑧ Huashixia-Yushu (2011), ⑨ Yanyuan-Mahu (2005), ⑩ Altay-Longmenshan (1989), ⑪ Xia Zayu-Gonghe (2001), ⑫ Golmud-Eji Qi (1992). Purple lines ($\mathrm{I_a}$, $\mathrm{I_b}$, $\mathrm{II_c}$, $\mathrm{II_d}$, and $\mathrm{III_e}$) denote the studied segments in basins, and white arrows and the dashed arrows denote the movement direction of blocks.

several DSS profiles with relatively complete resolution were completed near the northeastern Tibetan plateau margin and its peripheral basins (Figure 1), such as Dari-Lanzhou-Jingbian conducted in 1999 (②), Da Qaidam-Ruoqiang in the year 2000 (③), Golmud-Da Qaidam-Huahaizi in 2000 (④), Zizhong-Batang in 2000 (⑤), Barkam-Hezuo-Gulang in 2005 (⑥), Suining-Maoxian-Aba in 2010 (⑦), Huashixia-Yushu in 2011 (⑧), Yanyuan-Mahu in 2005 (⑨), and Xia Zayu-Gonghe in 2001 (⑪). A large number of high quality seismic data were collected, and some significant results were obtained (Jia and Zhang, 2008; Jia et al., 2010; Wang et al., 2003a, b; Li et al., 2002; Zhang et al., 2008; Gao et al., 2011; Zhang et al., 2011; Teng et al., 2013). These results lay a foundation for thorough study of the complicated crustal structures in the northeastern margin of the Tibetan plateau.

Differentiating between layers of continental crust, and fine structures in the subsurface, is mainly accomplished through the DSS method. A wide-angle reflection/refraction investigation can be used to image the velocity structures of near surface sediment cover, crystalline basement, inner crust and uppermost mantle. This basic but important method is useful in studying crustal structures and tectonics. In laterally homogeneous medium (velocity), the reflection from crustal interior interfaces and refraction travel time curves can be used to accurately infer layer velocity structures.

We chose the single shot seismic record section with complete observation and high signal-to-noise ratio (SNR) from different tectonic unit interiors, including ones within the northeastern margin of the Tibetan plateau (Longzhong basin, Qaidam basin, and the Songpan-Garze microblock, i.e., Zoige basin) as well as its peripheral basins (Ordos basin, Sichuan basin). We analyzed and extracted the seismic phase information which reflects the basin crustal tectonic features. We then computed the theoretical seismograms using the reflectivity method and compared them with real seismic record sections to identify fine crustal structures within these basins. Based on these results, we are able to contrast the crustal velocity structures and tectonic differences of the geological units, and use other detection results to further discuss evidence for deep crustal deformation. This deep crustal deformation is linked to crustal uplift and other dynamic processes in the northeastern margin of the Tibetan plateau.

3 Crustal structure classifications

The DSS record sections in the northeastern margin of the Tibetan plateau and its peripheral basins present three kinds of crustal seismic phase characteristics, which correspond to the peripheral stable Ordos and Sichuan basins, the Qaidam and Longzhong plateau basins, and the Zoige basin within the Songpan-Garze microblock in the northeastern margin (Ma, 1989).

3.1 Seismic phase characteristics and crustal structures in stable blocks

The DSS record sections in Ordos and Mesozoic Sichuan basin interior show similar seismic phase characteristics (Figures 2a$_1$, 2b$_1$, profile location ① (I$_a$), ⑦ (I$_b$) shown in Figure 1). The Pg phase is clear, and has a reduction travel time of 1–1.8 s, a track distance of 100–160 km, and its apparent velocity (6.0–6.3 km/s) increases in pace with offset, which presents stable upper crust velocity structural features. The reflected wave P_i phases are weak, showing steady travel times and weakly reflective transparent characteristics in crust. The PmP phases reflected from the Moho are very clear and have large amplitude, as well as simple seismic waveform, which indicates that the boundary between crust and mantle has strong wave impedance and velocity contrast. The reduction travel times of PmP overtake the reduction zero lines at offset 240–250 km, and its apparent velocity comes up to 7.0 km/s. The Pn phase refracted from the uppermost mantle is distinct and has long track distance, and its apparent velocity is 8.1–8.3 km/s.

The amplitude characteristics and travel times of seismic phases of the real records fit well with reflective seismogram methods (Figures 2a$_2$, 2b$_2$). The results show that the buried depths of the crystalline basement in the Ordos and Sichuan basins are 3 km and 6 km, respectively, and the sedimentary cover velocities are 2.5–5.2 km/s and 4.0–5.2 km/s, respectively. In the Sichuan basin, the sedimentary cover thickness and near-surface layer velocity are significantly greater than those in the Ordos basin, which suggests a more stable sedimentary environment existed in the Sichuan basin in the Middle and Late Mesozoic, and indicates the lithologic characteristic of high-velocity bedrock outcrop. In the Ordos and Sichuan basins, the upper crustal thickness is 12–14 km, and average velocity is 6.17–6.20 km/s, while middle crustal thickness is 12–14 km with average velocity of 6.40 km/s. The thickness of the lower crust in this region is 10–15 km, and the average velocity is 6.80–6.90 km/s. The total crustal thickness ranges from 40 km to 42 km with an average velocity of 6.12–6.26 km/s. The crystalline crustal interiors (from the crystalline basement to crust-mantle boundary) of the two basins show very good consistency. The medium velocity increases with depth. The average velocity is about 6.46 km/s, and there appear to be no lower velocity layers in crust. The crustal structures, which are simple and transparent along with high velocity lithologic features, present the typical cratonic characteristics of the peripheral blocks (Ordos and Sichuan basins) in the northeastern margin of the Tibetan plateau.

3.2 Basin structure characteristics

Mutual extrusion and collision among the blocks in the interior part of the Tibetan plateau formed marginal fold and thrust orogenic belts and corresponding basins within the interior of the plateau. The Qaidam basin is located between the East Kunlun-Altyn and Qilianshan, and trends to the east-northeast. The elevation in the basin interior ranges 2 700–2 900 m. It is the largest basin in the northeastern margin of the Tibetan plateau. The Longzhong basin is situated between the north edge fault of West Qinling fold belt and Liupanshan arcuate fault and its altitude is 1 700–2 100 m, which are the lowest elevations among basins in the northeastern margin of the Tibetan plateau. Both basins are Cenozoic in age (Ma, 1989; Ma, 2002).

The DSS record sections indicate that the Pg trace distances in the Qaidam and Longzhong basins come up to 150 km, while the reduction travel time is only 0.1–0.3 s in the Longzhong basin and reaches 1.3–2.8 s in the Qaidam basin. These results indicate that there are similar stable upper crust velocity structures in both basins, and large thickness differences in their respective

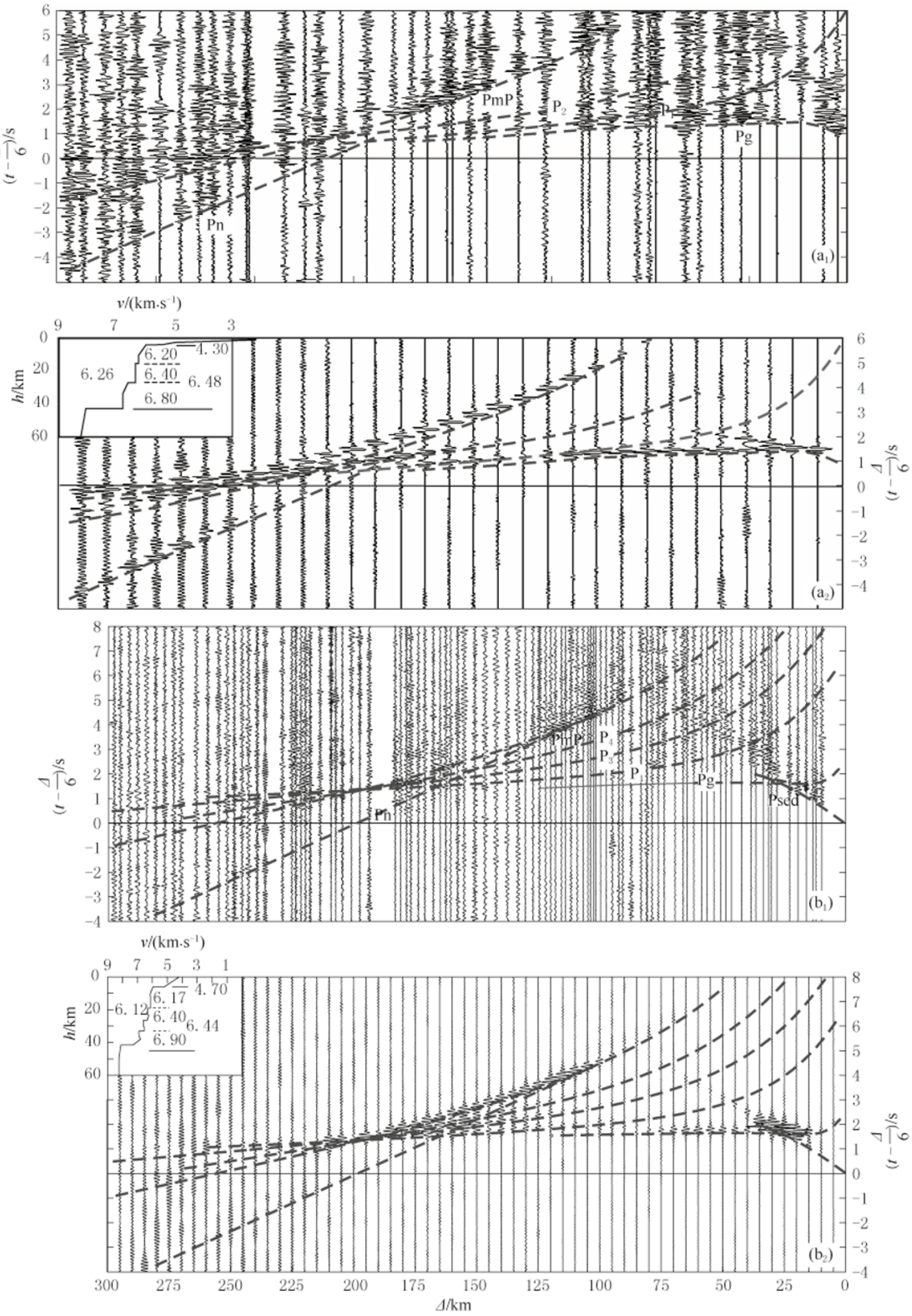

Figure 2 Recording section (a_1, b_1) and theoretical seismogram (a_2, b_2) in Ordos basin (a) and Sichuan basin (b). Δ and h denote distance and depth, respectively.

sedimentary covers. In the crustal interiors, the number of reflected P_i seismic wave groups increases and the energy is comparatively stronger. The trace distance of crustal seismic reflection wave groups is short in Qaidam basin and longer in the Longzhong basin, and the wave group apparent velocities of far shots all appear to rapidly decrease. The PmP phase in the Longzhong basin is clear and has strong amplitude with continuous 0.5–1.0 s, but becomes weaker in the Qaidam basin, although it can still be traced reliably. In both basins, the far shot apparent velocity is 6.3–6.5 km/s and decreases obviously compared to the Ordos basin and Sichuan basin. The refraction Pn phase from uppermost mantle is weak and it is difficult to perform long-range tracing (Figures 3a, $3b_1$, profile location ② (II_c) and ③ (II_d) shown in Figure 1).

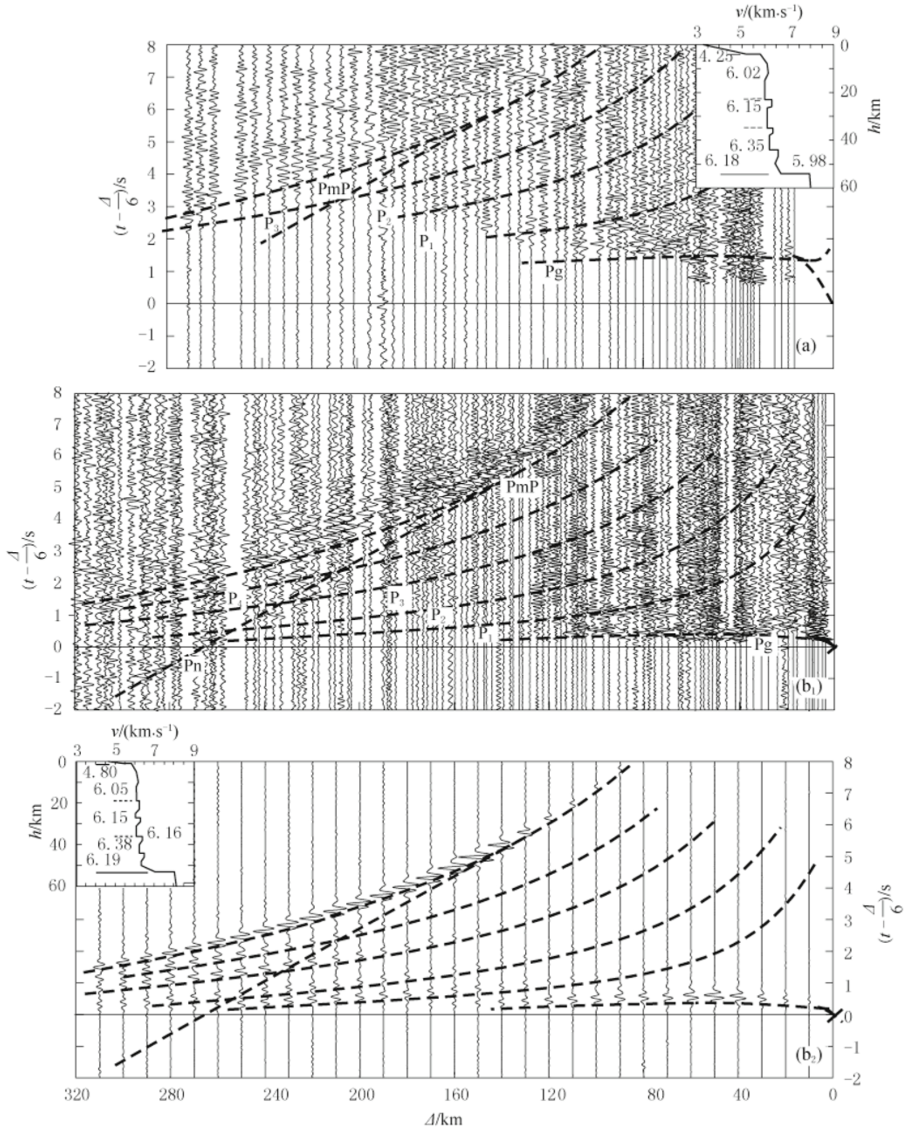

Figure 3 Recording section (a, b$_1$) and theoretical seismogram (b$_2$) in Qaidam basin (a) and Longzhong basin (b).

The crystalline basement depths in the Longzhong and Qaidam basins are 1 km and 3–6 km, respectively, and the sedimentary cover velocities are 4.5–5.2 km/s and 3.3–5.2 km/s, respectively. This indicates that the Cenozoic sedimentary cover in the Longzhong basin is very thin, while the Qaidam basin is a Cenozoic basin with stable and thick sedimentary cover. The two basins have similar crustal structures. The thickness of the upper crust is about 18 km and the average velocity is 6.03 km/s. There are two layers in upper crust. The upper layer thickness is ~8 km and medium velocity is 5.8–6.2 km/s. The thickness of the lower layer is about 10 km, which is a 6.0 km/s low velocity layer. The middle crustal thickness ranges 12–16 km, and the average velocity is 6.15 km/s, and there are 2–3 layers. The thickness of lower crust is 17–20 km and the average velocity is 6.37 km/s, and there are two layers. In the plateau, the number of interfaces in the middle and lower crusts increases and velocity slowly increases with depth, and there are obvious zones of interlayer low velocity, which ranges from 6.0 km/s to 6.5 km/s and presents layer structure characteristics of high velocity alternating with low velocity. The average crustal thickness in the Longzhong basin is 52 km and the average velocity is 6.16 km/s, and in Qaidam basin, the thickness of crust is 54 km and the average velocity is only 6.0 km/s, owing to the comparatively thick sedimentary cover. In two basins, the average velocity of crystalline crust is 6.18 km/s, which indicates that the basins in the northeastern margin of the Tibetan plateau (Figures 3a, 3b$_2$) share similar crustal structures.

3.3 The crustal structures of the Zoige basin within the Songpan-Garze microblock

Songpan-Garze microblock lies to the east of the Bayan Har block. Compared to the Longzhong and Qaidam plateau basins, the Zoige basin is within the Songpan-Garze microblock and has small area and high altitude (3 200–3 600 m), around which are the West Qinling, the Minshan-Longmenshan and the Bayan Har fold orogenic belts. Its surface is mainly covered with Early Mesozoic-Triassic rock and there is only a very thin surface of Quaternary sedimentary.

In the Zoige plateau basin, the DSS record sections show different seismic phase characteristics compared with other basins, which mainly presents complex crustal reflection P_i phases with strong energy and low apparent velocity. There are 5–6 groups of reflection phases. In general, the reflection phases appear at 50–280 km, and the later strong energy phase migrates to large offset with the increase of reflection interface depth. All phases reflected within the crustal interior show low apparent velocity features. At the offset ranging from 150 km to 250 km, the apparent velocity is only 6.5–6.0 km/s, and the strong seismic phases reflected from lower crustal interfaces even suppress or interfere with the PmP phase at the same distance. The Moho reflection of the PmP phase is weak, yielding a wave group that is not clear, with low apparent velocity (Figure 4a, profile location ⑥ (III$_e$) shown in Figure 1).

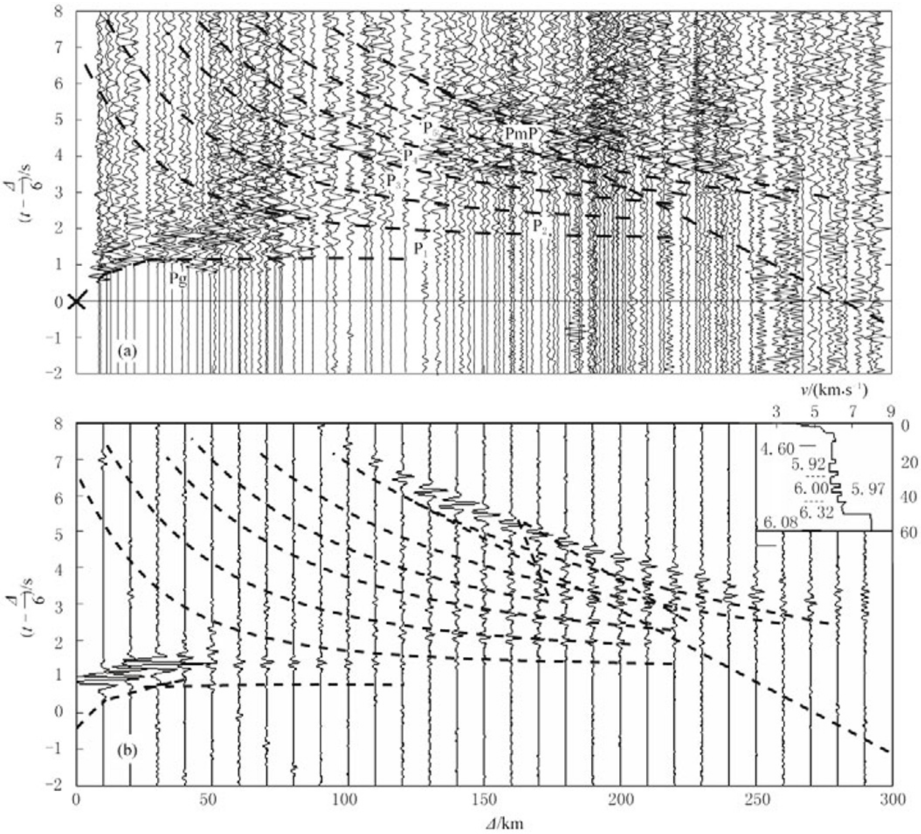

Figure 4 Seismic record section (a) and theoretical seismogram (b) in Zoige basin.

The depth to the crystalline basement in the Zoige basin is 2–4 km, and the sedimentary cover velocity is 4.0–5.4 km/s. The thickness of the upper crust in this region is 16–18 km, and the average velocity is about 5.92 km/s. The upper crust consists of two layers, the upper of which is a gradient layer and its thickness is ~7 km, with a medium velocity of 5.8–6.1 km/s. The lower part is a low velocity layer, the thickness of which is ~10 km, with an average velocity of 5.8 km/s. There are 2–3 layers in middle crust, the thickness of which is ~14 km and average velocity is 6.00 km/s. The thickness of lower crust is about 18 km and the average velocity is 6.32 km/s, and there are three layers. In the Zoige basin, the whole crustal thickness and its average velocity are 52 km, 6.00 km/s, respectively. The crystalline crust has thickness and average velocity of 49 km and 6.08 km/s, respectively. Compared to the Qaidam and Longzhong basins, the Zoige basin crust shows more prominent interfaces and low velocity layers as well as a relatively weak Moho velocity contrast, indicating structural characteristics consistent with strong transitions in the Zoige basin crust within Songpan-Garze microblock (Figure 4b).

4 Crustal structures

In order to further investigate the crustal structure features within the northeastern margin of the Tibetan plateau and its peripheral regions, we use the crustal velocity structures to divide the crust into discrete layers: the sedimentary cover and the upper, middle, and lower crusts in the crystalline crustal interior (Table 1). Crustal layering is mainly established on the basis of the different seismic phases on seismic record sectional drawing and the phase velocity reflects similar medium lithology (velocity). Figure 5 shows the PmP travel time curves and velocity structures in different blocks.

4.1 Contrast of reflective PmP travel time curves

Strong amplitude reflections from the Moho discontinuity, and reliable long range trace characteristics, allow the PmP phase to be accurately identified. The travel time curve reflects the averaged crustal velocity structure features. The PmP phase travel time curves of three different types of tectonic basins (the Sichuan basin, the Qaidam basin, and the

Table 1 Layer thickness (*h* in km) and average velocity (*v* in km·s^{-1}) in the northeastern margin of Tibetan plateau and its vicinity

Basins	Sedimentary cover		Crystalline crust								Average of crust	
			Upper		Middle		Lower		Average			
	h	*v*	*h*	*v*	*h*	*v*	*h*	*v*	*h*	*v*	*h*	*v*
Sichuan (I_b)	6	4.70	13	6.17	13	6.40	10	6.90	36	6.44	42	6.12
Qaidam (II_d)	4	4.25	18	6.02	12	6.15	20	6.36	50	6.18	54	5.98
Zoige (III_e)	3	4.60	17	5.92	14	6.00	18	6.32	49	6.08	52	5.97

Note: DSS profiles I_b, II_d and III_e in the table can be seen in Figure 1.

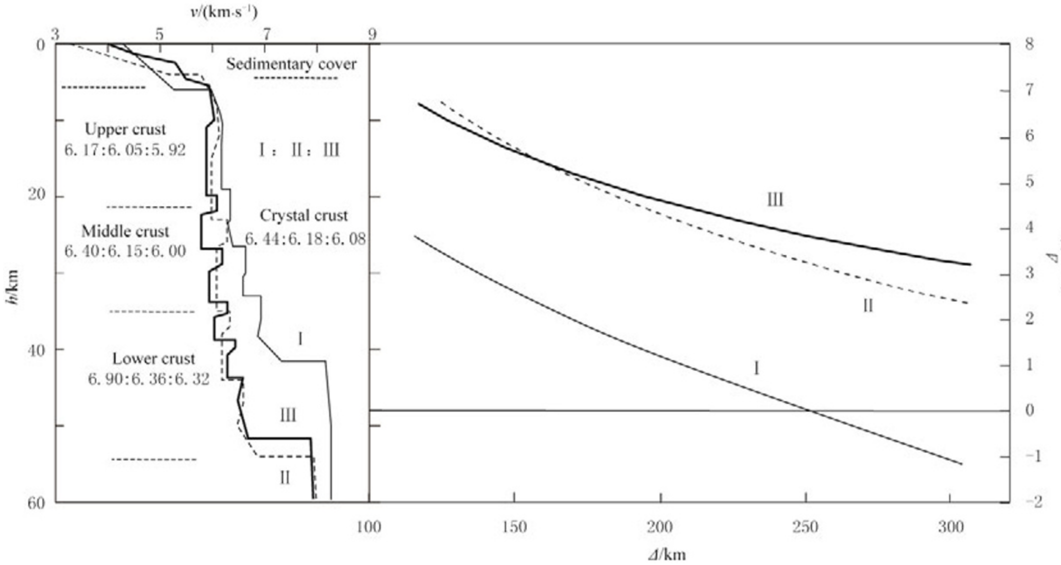

Figure 5 Travel-time curves of PmP and crustal velocity structures in the northeastern margin of the Tibetan plateau and its peripheral basins. I. Sichuan basin, II. Qaidam basin, III. Zoige basin.

Zoige basin) show that the reduction time of northeastern Tibetan plateau basins (shown with II and III in Figure 5) has large delays of 3–4 s relative to peripheral basins (shown with I in Figure 5). At long range offset, the apparent velocity decreases significantly and is more obvious in the Zoige basin. All of these factors indicate the rebuilding structure characteristics with thickened plateau basin and low velocity structure.

4.2 Sedimentary cover and basin properties

The thickness of the sedimentary cover in the Sichuan basin is 5–7 km, and the average velocity is 4.70 km/s. The near-surface velocity is considerably higher and ranges from 3.5 km/s to 4.2 km/s, indicative of a stable Mesozoic sedimentary basin. The thickness of the sedimentary cover in the Qaidan basin is about 3–6 km, and its average velocity is approximately 4.2 km/s. The velocity near the surface, which ranges from 2.0 km/s to 3.5 km/s, has a comparatively large variation. In the Zoige basin, the sedimentary cover thickness is 2–4 km, and the average velocity is 4.6 km/s. The Quaternary sedimentary cover on the surface is very thin, mainly as a result of the outcropping of Triassic strata during Early Mesozoic with relatively high velocity of 3.2–4.2 km/s. The strong velocity gradient with high velocity in the sedimentary cover shows the specific structural characteristics in Mesozoic Zoige sedimentary basin (Jia et al., 2010).

4.3 Transformation of crystalline crust

The crystalline crustal thicknesses of the Sichuan, Qaidam and Zoige basins are 36 km, 50 km and 49 km, respectively, and their average velocities are 6.44 km/s, 6.18 km/s and 6.08 km/s, respectively. The crystalline crusts of basins within the northeastern Tibetan margin were significantly thickened compared to the crust found in the peripheral basins. The average velocity of the crystalline crustal interior clearly decreases by 0.3–0.4 km/s, which accounts for a relative velocity difference up to 5%.

4.4 Brittle deformation of upper crust

In the Sichuan, Qaidam and Zoige basins, the buried depth of the upper crust ranges from 3 km to 23 km, the thicknesses of which are approximately 13 km, 18 km and 17 km, respectively and the average velocities are 6.17 km/s, 6.05 km/s and 5.92 km/s, respectively. The upper crustal thickness in plateau basin is slightly larger than that in the peripheral basins, and the difference in the average velocity is 0.1–0.2 km/s while the relative difference is only 1.5%–3.5%. These data indicate that micro lithological changes, micro rupture and brittle deformation occur in the upper crust of the plateau basins.

4.5 The low velocity and plasticization of the lower crust

The buried depth of lower crust in the Sichuan, Qaidam and Zoige basins is 33–55 km, the thicknesses of which are about 10 km, 20 km, 18 km, respectively, with average velocities of 6.90 km/s, 6.38 km/s and 6.36 km/s, respectively. The lower crust of the plateau basin is thickened greatly, and there are obvious low velocity structures. The average velocity difference is 0.50–0.60 km/s, while the relative difference is 7.2%–8.7%. This indicates significant lithologic variation existence, as well as possible plasticization structure in the lower crust of the northeastern margin basin.

Wang et al. (2007) applied the spectral ratio method to the PmP seismogram records to estimate Q_{P} in lower crust, obtain lower Q_{P} (100–300) values beneath the western Sichuan plateau and high Q_{P} (1 000 or more) beneath the Sichuan basin. They suggest that the high attenuation results from lower crustal flow caused by the large lower crustal thickness beneath the western Sichuan plateau.

4.6 The brittle-plastic transition in the middle crust

The buried depth of the middle crust in the Sichuan, Qaidam and Zoige basins is 20–36 km, the thickness of which ranges 12–15 km, with average velocities of 6.40 km/s, 6.15 km/s and 6.00 km/s, respectively. Compared to the peripheral basins, the plateau basins have many low velocity structures. The average velocity difference is 0.25–0.40 km/s while the relative difference is about 3.5%–6.2%. This difference suggests the presence of semi-brittle and semi-plastic crustal material, as well as a brittle-plastic transition zone within the basins of the northeastern margin of the Tibetan plateau.

4.7 The main regions of plateau basin thickening and medium structure variations

Compared to the peripheral basins, the crustal thickness of the northeastern margin of the Tibetan plateau's interior increased by 10–15 km and average medium velocity decreased by about 5%. In the crystalline crustal interior, the average thickenings of the upper, middle and lower crusts are 3–5 km, 1–3 km and 5–10 km, respectively. The average velocity reduction in the upper, middle and lower crusts are 0.2 km/s, 0.3 km/s and 0.6 km/s and the relative velocity reductions are 2.5%, 4.7% and 7.8%. These structural features indicate that in the northeastern margin of the Tibetan plateau, the crustal thickening and medium structural variations mainly occur in lower crust. The plateau crustal medium properties change from brittle to plastic with depths. In plateau lower crust (35–55 km in depth), the medium velocity decreases greatly, suggesting intensity reducing of the lithology and possible plastic rheological characteristics.

5 Discussion and conclusions

During convergence of the Indian and Eurasian plates, the Tibetan plateau crustal thickness rapidly increased relative to its peripheral stable cratonic blocks (e.g., the Tarim, the Great North China, the Yangtze, the thicknesses range 38–42 km). The crustal thickness of the Qiangtang block in northern Tibet and the Lhasa block in southern Tibet increased by about 25–35 km while in Songpan-Garze, the Qaidam and Longzhong blocks of the northeastern margin of the Tibetan plateau increased about 10–15 km. Combined with GPS observations of crustal movement, and DSS investigation results, we plan to show that there are different crustal thickening mechanisms between the Tibetan plateau interior and its northeastern margin.

5.1 Plateau basin properties and crustal structures along the northeastern margin

The altitudes of the peripheral Sichuan and Ordos basins in northeastern margin are 400–600 m, and 1 000–1 400 m, respectively, while the plateau basin elevations of Longzhong, Qaidam and Zoige within the Tibetan plateau are 1 800–2 200 m, 2 700–2 900 m, and 3 300–3 600 m, respectively. The crustal structures show that there are strong medium velocity structure transitions in the crustal interior with increasing plateau-basin altitude. The Qaidam basin has a surface area of approximately 2.5×10^5 km^2, and the DSS record sections show a clear PmP phase, while the intermediate reflection phases P_{1-3} are relatively weak (Figure 3a). The Zoige basin has a surface area of about 3.0×10^4 km^2, where the PmP phase is interfered and has weak energy while the crust interior seismic phases P_{1-5} reflected from multiple interfaces are relatively strong (Figure 4a). The average crystalline crustal velocity in the Qaidam basin (6.18 km/s) is significantly greater than that in Zoige basin (6.08 km/s). This result suggests that during the tectonic extrusion deformation processes among these blocks, the comparatively large Qaidam basin had a certain ability to resist the deformation. There is relatively minor deformation within the crust in this basin, while in the comparatively small Songpan-Garze microblock, strong deformation in the interior presents the structural properties of a remnant basin (Figures 1 and 5).

5.2 The relationship between block structures, crustal thickening in Tibetan plateau and the peripheral tectonic stress field

The main active faults in the Tibetan plateau and the current crustal movement GPS observations (Zhang et al., 2002) indicate that the Ganges River plain is moving away from the northern edge of the Indian plate, and extruding towards the Tibetan plateau at a rate of 45 mm/a in the direction NE20°. Additionally, in the middle of the Tibetan plateau (to the west of 90°E), the crustal movement direction extends to the southern margin of the Tarim basin, and although it has hardly changed direction, its rate has been reduced to 15 mm/a. That is to say, about 2/3 of the relative plate movement is accommodated by crustal shortening and thickening along with peripheral orogenic uplift of the Lhasa and Qiangtang blocks as main bodies in the mid-west of the Tibetan plateau. To the east of 90°E, the crustal movement is in the north-south direction, and toward north, the northern component gradually decreases, while toward the east, the ratio of eastern motion component to the northern gradually increases. It seems to form a belt of eastward flowing material in the northeastern part of Tibetan plateau, which is mainly along the northeastern margin of Mani-Yushu-Xianshuihe fault (trending in NE75°, and its east-west slip rate is about 25 mm/a). The plateau geological structures show that the Tertiary strata (E_{1-2}) in the Lhasa block are widely distributed to the west of 90°E, mainly consisting of Early Himalaya granite, and Late Paleozoic-Carboniferous strata to the east of 90°E (Ma, 2002). It indicates that beneath the Indian-Eurasian plate collision, the motion modes of the mid-west block of the Tibetan plateau are different from the eastern block, and that differences in sedimentary tectonic environment exist.

During the Yushu earthquake scientific expedition conducted by Geophysical Exploration Center, China Earthquake Administration (CEA) in 2011, a 500 km-long Huashixia-Yushu-Nangqen DSS profile, which crosses western Bayan Har block and reaches northeastern Qiangtang block, was carried out (profile ⑧ in Figure 1), and very good seismic records were obtained. The preliminary results show that the crustal thickness of western Bayan Har block is about 62 km, and has slowly thickened an additional 10 km relative to the eastern Zoige basin (about 450 km away). The crustal thickness rapidly increases to 72 km near the

Yushu fold zone, where the Bayan Har block meets the Qiangtang block. The results from the Maqen-Lanzhou-Jingbian DSS profile (profile ② in Figure 1) indicate that the crustal thickness of the middle-north Bayan Har block (Dari) is about 60–63 km along its northern edge (Li et al., 2002). It is suggested that there is comparatively homogeneous crustal structure in the Bayan Har block interior, while the crust is obviously thicker along its southwestern boundary (the Mani-Yushu-Xianshuihe fold belt), and there is a rather small variation of crustal thickness along the northeastern boundary (the western Qinling fold zone; Figure 1).

To sum up, the crustal tectonic deformation in the Tibetan plateau is closely related to the principal compressive tectonic stress field and motion direction of the Indian plate. The central belt of eastward-flowing crustal material along the boundary between the Qiangtang and the Bayan Har blocks (Mani-Yushu-Xianshuihe fold belt), and differences in crustal thickness at its two sides, divide the different tectonic characteristic areas of the northeastern margin of the Tibetan plateau into the middle-western plateau and its southeastern area.

The crustal structures of the different tectonic blocks (Zoige, Qaidam and Longzhong basins) in the interior of the northeastern margin of the Tibetan plateau suggest that their upper crusts mainly undergo brittle deformation and minor thickening, while the rheologically weak lower crust is the main region of thickening. There is wholesale block movement in this region, and the associate crustal shortening is the main deformation mechanism. The crustal movement of the southeastern plateau converts clockwise rotation around the eastern Himalaya syntaxis, where crustal material is southward flowing, and the crustal thickness rapidly decreases. In Yanyuan of southwestern Sichuan (DSS profile ⑨ in Figure 1), the crustal thickness is about 48 km, while in Longling of southwestern Yunnan province, it is only about 37 km (Kan and Han, 1992). In the mid-west of the Tibetan plateau, the crust is greatly thickened, and its thickening mechanism is still under great debate. Though the teleseismic receiver function method can be used to infer the deeper lithospheric structural patterns, it does not have enough resolution to reveal crustal structures (Zhao et al., 2010). The artificial deep seismic reflection survey can only be used to investigate the crustal tectonic patterns and as its limitations, including the inability to determine velocity structures of deep material. The DSS method is the best way to investigate crustal velocity while so far, the most distant seismic record for a single shot is about 350 km. These data mainly record crustal reflection phases and no refraction phase data from farther distances that reveal lower crustal structures were collected (Zhao et al., 2001). It is difficult to use a single model to interpret plateau thickening mechanisms, as there are differences in the motion mode and the thickening scale in the vast Tibetan plateau and in its interior.

Based on the DSS method, we need to deploy a more complete observation system to investigate the crust with 60–80 km thickness, the offset of which is at least up to 500 km. That is to say, to record comparatively complete seismic refraction phases coming from entire crust, especially the lower crust, and to detect fine lower crustal structures directly. To build more reasonable crustal thickening mechanism models in the Tibetan plateau, it is also very important to investigate the coupled relationships among the plateau interior basins, marginal fold zones, the peripheral stable cratonic basins as well as its tectonic implications on the deep dynamic mechanisms.

5.3 Conclusions

Using the DSS method, and through contrast investigation for the crustal structures in the northeastern margin of the Tibetan plateau and its peripheral basins, we analyzed the plateau basin crustal lithologic variation with depths as well as the crustal uplift and thickening mechanism.

The main crustal structure characteristics of the plateau basins in the northeastern margin of the Tibetan plateau reveal that the upper crust undergoes brittle deformation, the lower crust deforms plastically with lower velocity, and the middle crust shows a brittle-plastic transition zone. The crustal thickening and medium weakening of the plateau basins mainly takes place in lower crust.

The plateau crustal transformation is related to properties of the tectonic blocks in this region. The higher the altitude, the stronger the lithologic transform in the crustal interior. The smaller the block, the stronger the lithologic transform in the crustal interior.

In the Tibetan plateau, the blocks with different crustal thickening characteristics related to block motion modes indicate that the Mani-Yushu-Xianshuihe fold belt along the boundary between the Qiangtang and the Bayan Har block divides the different plateau thickening tectonic environments into the middle-western plateau, the northeastern margin and the southeastern plateau. The DSS exploration with significant higher resolution data is an important method for investigation of the fine Tibetan plateau crustal structures and thickening mechanisms.

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