Lithospheric Evolution and Geodynamic Process of the Qinghai-Tibet Plateau: An Inspiration from the Yadong-Golmud-Ejin Geoscience Transect

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Abstract The Tibet Geoscience Transect (Yadong-Golmud-Ejin) has revealed the basic structures, tectonic evolution and geodynamic process of the lithosphere of the Qinghai-Tibet plateau. The evidence of northward thrusting of the Indian plate beneath the Himalayans on the southern margin and to southward compression of the Alxa block on the northern margin has been found. They were the driving forces causing the plateau uplift. The plateau is a continent resulting from amalgamation of eight terranes. These terranes are separated by sutures or large-scale faults, and different terranes have different lateral inhomogeneities and multi-layered lithospheric structures. At depths of about 20–30 km of the crust in the interior of the plateau there commonly exists a low-velocity layer. It is an uncoupled layer of the tectonic stress; above the layer, the upper crustal slices were thrust and overlapped each other and the rocks underwent brittle deformation, thus leading to shortening and thickening of the upper crust. Below the layer, the lateral change of the structure of the lower crust varies most greatly and ductile deformation occurs. The lower crust velocity of southern Tibet shows the reversed feature; whereas the lower crust velocity of northern Tibet increases and displays strong gradient variation and the character of the double Moho. On the whole, the Moho of the plateau is greatly undulatory. Although the crust of the Qinghai-Tibet Plateau has a great thickness, the lithosphere does not thicken markedly. The plateau is in a state of bi-directional compression. The unstable change of the Moho, the interaction between the crust and mantle and between the lithosphere and asthenosphere caused by the sinking of the lithospheric mantle and the strike slip and extension of the crust are the major dynamic factors for maintaining the present height and scope of the Qinghai-Tibet Plateau.

Key words: Qinghai-Tibet Plateau, lithosphere, geotransect, continental dynamics

Since 1980, various departments concerned in China have independently or in cooperation with foreign countries carried out large-scale geological and geophysical investigations and accumulated a wealth of data. On the basis of these investigations we separately compiled the Yadong-Golmud geoscience transect (1986–1990) and the Golmud-Ejin geoscience transect (1991–1995) according to the unified planning of the Chinese National Committee for the International Lithosphere Program (ILP) and the requirements of the guidelines for the global geoscience transect projects issued by the Inter-Union Commission on the Lithosphere (ICL). The two transects link up to form the Yadong-Golmud-Ejin geoscience transect passing through the whole Qinghai-Tibet Plateau, which is called the TGT (Tibet Geoscience Transect) for short.

In compiling this transect, large amounts of additional geological and geophysical investigations were conducted in regard to key geoscience problems. Geophysical studies included heat flow and magnetelluric sounding, as well as gravimetry and magnetics. Explosion seismic sounding was carried out in the Golmud-Ejin transect domain and near seismic reflection profiling on the northern margin of the Qilian Moutnains. Through field investigations and comprehensive studies, we have obtained some new achievements and ideas and revealed the structure, tectonic evolution and geodynamic process of the lithosphere of the Qinghai-Tibet Plateau (Project Group of the Geoscience Transect from Yadong to Golmud, 1990; Project Group of the Geoscience Transect from Golmud to Ejin, 1995; Wu et al., 1991; Wang et al., 1997). This paper briefly describes the

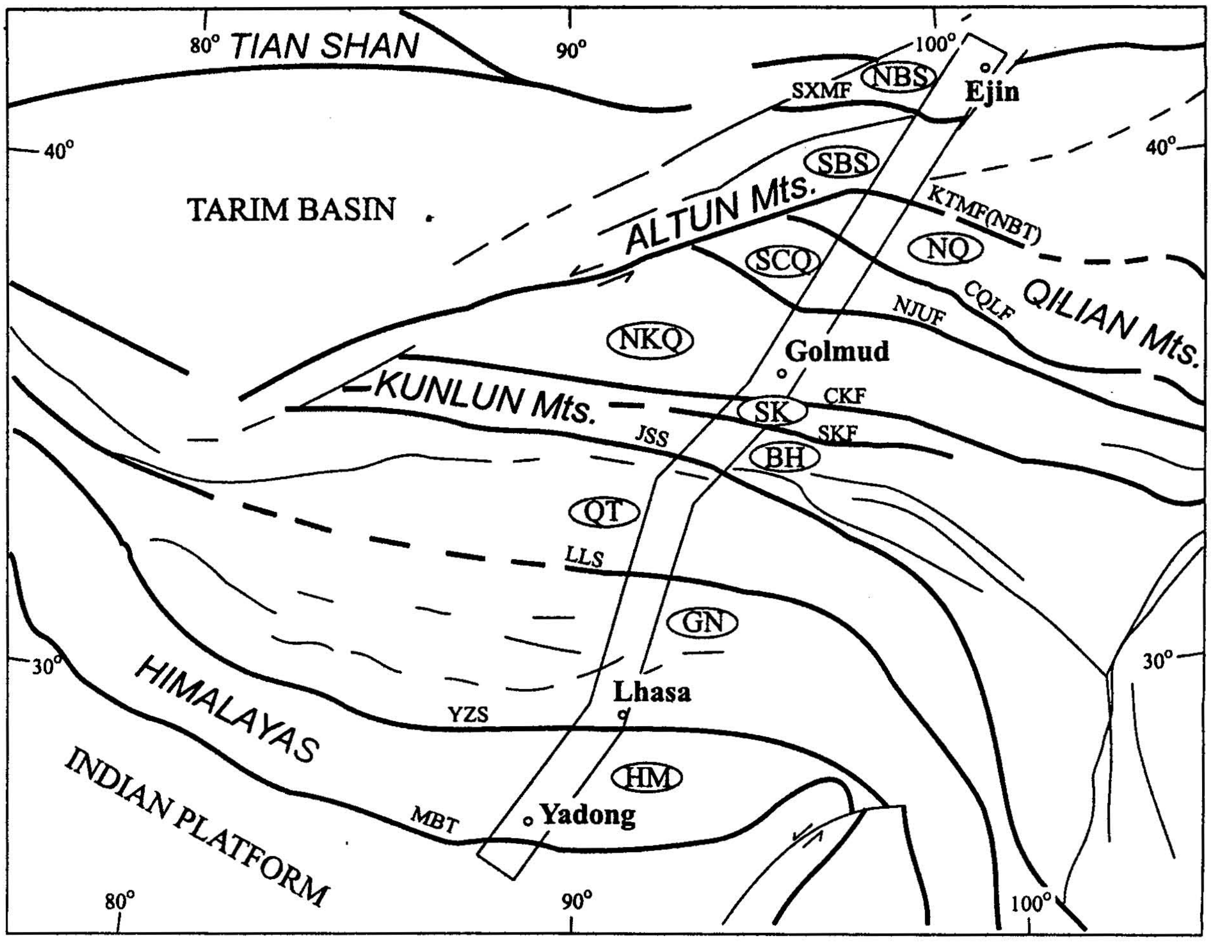

Fig. 1. Location and terrane tectonics of the TGT.

(NBS): North Beishan terrane; SXMF: Shibanjing-Xiaohuangshan Mountain Fault; (SBS): South Beishan terrane; KTMF= Kuantan Mountain Fault, NBT= North Boundary Thrust; (NQ)= North Qilian terrane; CQLF= Central Qilian Fault; (SCQ)= South-Central Qilian terrane; NJUF= North Jun Ul Fault; (NKQ)= North Kunlun-Qaidam terrane; CKF= Central Kunlun Fault; (SK)= South Kunlun terrane; SKF= South Kunlun Fault; (BH)= Bayan Har terrane; JSS= Jinsha River Suture; (QT)= Qiang-Tang terrane; LLS= Lungmu Co-Lancang River Suture; (GN)= Gangdise terrane; YZS= Yarlung Zangbo Suture; (HM)= Himalaya terrane; MBT= Main Boundary Thrust.

main achievements.

1 Tectonic Framework of the Plateau

Sandwiched in between the Tarim, North China, Yangtze and Indian rigid blocks, the Qinghai-Tibet Plateau is not only a unified plateau geomorphically but also an independent system in terms of the geophysical field and lithospheric structure, forming a relatively independent tectonic system. The plateau itself is also a continent resulting from amalgamation of terranes. The transect extends for about 2400 km from the Ganges plain in the Indian shield northwards through the Himalayas, various orogenic belts and the Qaidam basin in the interior of the Qinghai-Tibet Plateau and the Qilian orogenic belt and Hexi Corridor basin on the northeastern margin of the plateau, across the Beishan up to Ejin on the southern margin of the Siberian plate near the Sino-Mongolia border.

Ten terranes may be distinguished along the transect (Wu et al., 1989, 1991a, 1993; Gao et al., 1995, 1996); they are separated by sutures or large-scale faults. From north to south the names of the terranes and suture zones or major faults are shown in Fig. 1.

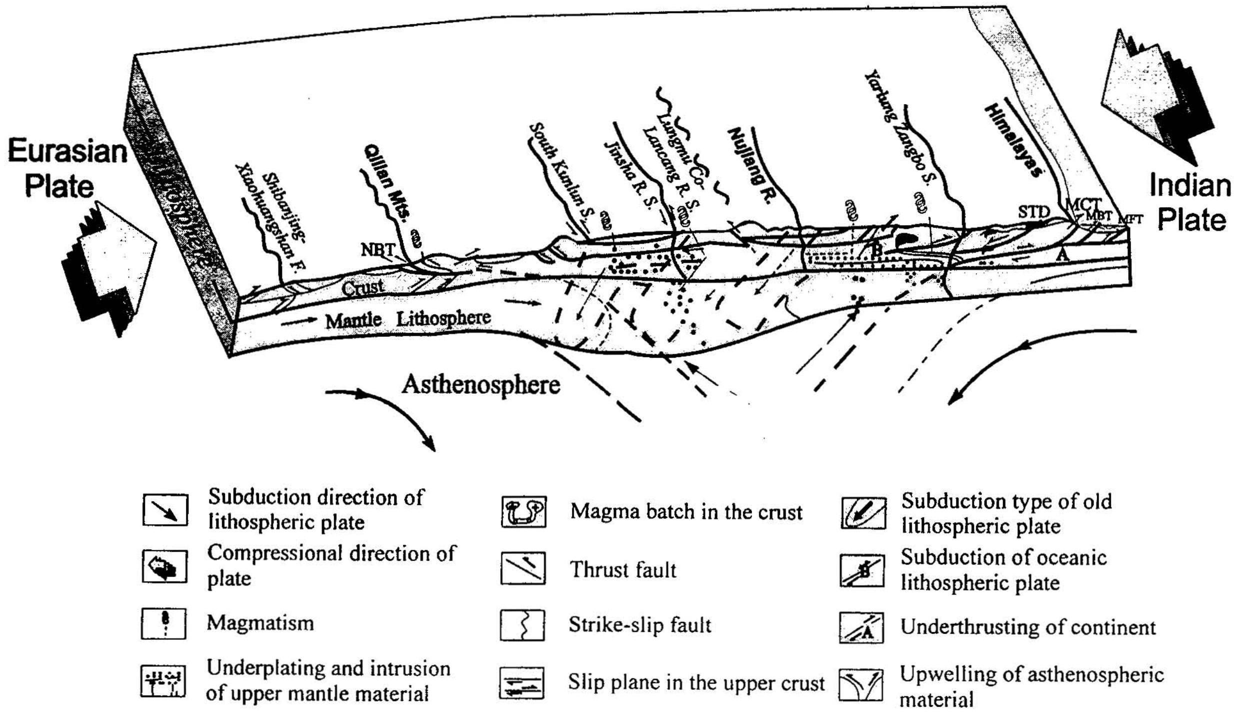

Fig. 2. Geodynamic model of the uplift of the Qinghai-Tibet Plateau.

STD= South Tebitan Detachment; MBT= Main Boundary Thrust; MCT= Main Central Thrust; S.=suture; F.= fault; R.=river.

2 Structure of the Lithosphere of the Plateau

Geophysical data indicate that the lithosphere of the Qinghai-Tibet Plateau is characterized by vertical and lateral inhomogeneity and multi-layered structure and that different terranes have different layered structures (for details see Fig. 3 in Wu et al., 1991b, and Fig. 3 in Gao et al., 1995).

2.1 Low-velocity (high-conductivity) layers

At a depth of about 20 km of the crust in the interior of the plateau there commonly exist low-velocity layers with a velocity of 5.60–5.80 km/s and a thickness of 5–10 km. It is inferred that they are mainly water-bearing detachments and locally might be produced by the molten magma chamber. The magnetotelluric sounding has also revealed the existence of high-conductivity layers in the crust, which extend along the entire transect line but have a relatively sharp relief. In the upper crust, the location of the high-conductivity layer is close to that of the low-velocity layer; whereas in the lower crust it generally inclines. The resistivity of the high-conductivity layer commonly varies from 5 to 10 Ω·m. In the middle-lower part of the lower crust (below 25 km in depth) of the Himalayas a north-dipping and continuous high-conductivity layer has been found. This layer extends southwards to link with the MCT and MBT, implying that the layer is likely to represent the tectonic track along which the Indian plate is subducted beneath the Himalayas and reached the mantle beneath the Yarlung Zangbo suture zone.

2.2 Changes of the Moho and crustal thickness

The changes of the Moho and crustal thickness of the Qinghai-Tibet Plateau show the following distinctive features.

(1) On the whole the Moho of the plateau is relatively shallow on the north and south sides and relatively deep in the interior. It deepens gradually from about 35 km below the Ganges plain of India, 61 km below the Higher Himalayas and 78 km below the Tethys Himalayas to a maximum of 80 km below the

Qiangtang area, and then it rises to a depth of 63 km below the Kunlun Mountains and to about 58 km below the Qaidam basin; and in the Qilian Mountains it again deepens to more than 60 km, showing the characteristics of a mountain root. In the southern part of the plateau the Moho is greatly undulatory and is displaced in many places. The throws across the suture zone or gigantic faults may reach 10 km or so.

(2) The overlapping phenomenon of the Moho often appears on the plateau, particularly in its southern part. For example, the Moho north of the Yarlung Zangbo River occurs as interrupted slices arranged en chelon, implying that the deep part of the crust has undergone strong compression.

(3) There exist two wide-angle reflecting horizons at about 55 km and 75 km below the Gangdise Mountains in northern Tibet respectively. The velocity between the two horizons averages 7.40 km/s. It is inferred that the shallow and strong reflecting horizon represents the old Moho which was uplifted owing to compression, while the deep and relatively weak reflecting horizon might be the newly formed Moho.

2.3 Thickness of the lithosphere

The results of explosion seismic sounding and natural seismic sounding show that although the crust of the Qinghai-Tibet Plateau has a great thickness, the lithosphere does not thicken markedly: the average thickness of the lithosphere is 100–120 km in the south and 110–130 km in the north, and undulates locally.

The general trend of undulation of the high-conductivity layer of the upper mantle revealed by magnetotelluric sounding is close to that of the thickness of the lithosphere interpreted by natural seismic sounding, but the average buried depth of the former is relatively great, being 140 km on the north and south margins of the plateau and up to 200 km in the interior of the plateau.

2.4 Lateral change of the physical structure of the lithosphere

The physical structure of the lithosphere of the plateau shows conspicuous lateral change. Especially the wave velocity tends to be attenuated on the terrane boundary. The average velocity is generally 6.20–6.30 km/s in the crust and 8.10–8.20 km/s on the top of the upper mantle. The average crustal velocities of the Himalayas and the Qilian Mountains are slightly lower than those in other terranes.

The velocity of the upper crust varies relatively greatly. The average velocity beneath the Qaidam basin is 5.70 km/s as very thick Meso-Cenozoic sediments are developed there, while the average velocity for other terranes is lower than 4.00 km/s as the thickness of Cenozoic sediments there is less than 4 km. But the average velocity of the upper crust below the Qilian Mountains is 5.51–5.60 km/s, being lower than that below the Qaidam basin. The velocity is generally 5.80–6.00 km/s for areas where the upper crust was composed dominantly of Precambrian metamorphic series and granites of different ages.

The mid-crustal velocity is relatively stable, generally 6.30–6.50 km/s, but it is relatively low below the Central Qilian Mountains and reaches a minimum of 6.10 km/s below the Har Lake area. The second low-velocity layer is found at a depth of about 50 km below northern Tibet, with a velocity of 6.10–6.30 km/s. The velocity of the lower crust varies most greatly. The lower crust velocity of the Himalaya terrane shows the reversed feature; the lower crust velocity of the Gangdise terrane shows strong gradient variation; the lower crust velocities of the Bayan Har and South Kunlun terranes show weak gradient variation; the lower crust velocities of the Qaidam basin and south-central Qilian terranes are normal; the lower crust velocity of the North Qilian terrane is relatively low.

The resistivity in the lower lithosphere, i.e. near the Moho and below it, shows very distinct variation. The outstanding example is the the Himalaya terrane. With the high-conductivity layer within the crust as the boundary, the resistivity is as high as 10 000 Ω·m south of it, while north of it the resistivity is only 1000–3000 Ω·m, suggesting that the Indian shield plunges from the foot of the Himalayas northwards into the Himalaya terrane. The similar phenomenon also appears in the Qilian Mountains, where the resistivity of the lower lithosphere is also high below the mountain margins and low below the central part.

3 Tectonic Evolution of Various Tarranes of the Plateau

Palaeomagnetic data (Dong et al., 1991, 1995) and study of biogeographical provinces (Liu et al., 1992; Chen et al., 1996) indicate that all terranes of the Qinghai-Tibet Plateau were located in the south-latitute region during the Early Palaeozoic. The North Qilian terrane is an ocean-island mixing mass. It converged with the South-Central Qilian terrane approximately in the terminal Ordovician. They crossed the equator and lay in the north-latitude region in the Silurian and again migrated southwards obviously in the period from the Silurian to Carboniferous.

The North Kunlun-Qaidam terrane crossed the equator approximately in the Late Devonian and was located in a region of latitude 20°N in the Late Carboniferous. It remained at this palaeolatitude relatively stably till the Triassic. There are still different views as to whether an ocean basin existed between Qaidam and South-Central Qilian. One of the views holds that the existence of eclogite implies that plate collision had taken place there and that intracontinental subduction continued to operate during the Early Mesozoic (Yang and Deng, 1994). Another view proposes that since no typical oceanic crustal rocks such as ophiolites have been found there, an ocean basin did not exist, and that at most there occurred only a deep-water aulacogen which closed at the end of the Ordovician (Liu et al., 1995).

The North Kunlun-Qaidam terrane converged with the South Kunlun terrane at the end of the Carboniferous and drifted to the northern Hemisphere in the Early Triassic. From the end of the Triassic to the Early Jurassic, the South Kunlun terrane converged with the Bayan Har and Qiangtang terranes. From the Late Jurassic to Early Cretaceous, the Gangdise terrane converged with the Qiangtang terrane. Finally, in the Late Cretaceous to Palaeogene, the Himalaya terrane converged with the Gangdise terrane. Then a unifying continent was formed in the realm of the Qinghai-Tibet Plateau, reflecting the evolutionary process of continuous accretion of the Eurasian continent.

4 History of the Plateau Uplift

The Qinghai-Tibet Plateau started a new stage of gradual crustal shortening and thickening and unceasing uplift of the plateau with the gradual closure of the Neo-Tethys and the convergence between the Indian and Eurasian plates after their collision in the Late Cretaceous to Eocene. The plateau uplift progressed through a complicated process of sympathic equilibrium of uplift and erosion, alternation of tectonic uplift and isostatic uplift and transition from slow uplift to rapid uplift (Li, 1995). The uplift occurred in three stages.

4.1 Stage of uplift due to subduction and collision

During this stage, mainly because of northward subduction and compression of the Indian plate including the Himalaya terrane, the Gangdise terrane was uplifted and an island arc-type volcanic-plutonic rock belt orginated; a "Gangdise molasse belt" was formed at the southern foot of the Gangdise Mountains. In this stage the elevation of the Gangdise Mountains was about 1000–1500 m above sea level.

During the Palaeogene, the northern and eastern parts of the plateau were represented by an uplift-erosion area. Large-scale strike-slip faulting gave rise to a series of pull-apart basins, in which were accumulated very thick evaporite-bearing fluvial-lacustrine red clastic rocks.The northeastern part of the plateau was then a few hundred metres above sea level, while the mountains might be as high as about 2000 m above sea level.

4.2 Stage of uplift due to convergence and compression

At the end of the Eocene, convergence between the Indian and Eurasian plates was accomplished, and continuous northward push and compression of the Indian-Australian plate and hindrance of rigid blocks in the northern and eastern parts of the plateau resulted in large-scale crustal shortening and thickening and sustained slow uplift of the plateau.

Intracontinental convergence gave rise to large-scale thrusts, nappes and detachments in the Himalaya region, accompanied by polyphase intrusion of leucogranite. Owing to rapid uplift of the Himalaya region, clastic rocks represented by the Muli Group were formed at the southern foot of the Himalayas and an abyssal alluvial fan was initiated in the Bay of Bengal. Then the height of the Himalayas was about 1000 m above sea level and the height of the main peak zone might reach 2000–3000 m.

A range-basin topographic framework was formed in the interior of the plateau. In basins were accumulated fluvial-lacustrine coal- and oil-bearing clastic rock sequences and intermediate-basic volcanic rock series. At the end of the Miocene, there appeared a peneplain surface on the Qinghai-Tibet Plateau. The plateau then was 1000–1500 m above sea level and some mountains and peaks on the plateau might attain 2000–3000 m.

4.3 Stage of uplift due to isostatic adjustment

Owing to stress relaxation and isostatic adjustment or the effect of hot buoyancy caused by upwelling of materials from the asthenosphere and other deep-seated effects that have not been demonstrated, at the beginning of the Pliocene the plateau entered a new stage marked mainly by large-amplitude en-masse uplift after uplift and planation in the previous stage, and the uplift velocity had a tendency to become more and more rapid.

In the Himalaya region, strong folding, faulting and crustal uplift gave rise to regional metamorphism, migmatization and intrusion of leucogranite. The famous Siwalik molasse belt originated in the front of the Himalayas. During the Pliocene to early Pleistocene, the elevation of the Himalaya region was about 2000–3000 m above sea level. Its uplift to the present height is a geological event that occurred in the middle Pleistocene.

In the interior of the plateau, isostatic adjustment brought about large-amplitude rapid uplift. Very thick Pliocene-early Pleistocene molasse sediments are distributed in the front of the Kunlun Mountains and at the northern foot of the Qilian Mountains. The Pliocene-early Pleistocene sediments containing temperate floras in the eastern part of the plateau have been mostly uplifted to the summits of the high mountains at an elevation of more than 4000 m. The features of the reverse cycle of the Pliocene-early Pleistocene molasse sediments in the front of the Himalayas, on the southern margin of the Tarim basin and at the northern foot of the Qilian Mountains also indicate that the plateau has gone through a process from slow uplift to rapid uplift since the Pliocene.

5 Dynamic Process of the Plateau Uplift

The driving force causing the plateau uplift was mainly derived from the compressive stress resulting from the northward motion of the Indian plate and its subduction beneath the Himalaya terrane (see Fig. 2). The track of the subduction has been traced by the high-conductivity layer found by the magnetotelluric sounding (see Figs. 3 and 5 in Wu et al., 1991b). In addition, the plateau was also subjected to the southward compression of the Tarim and Siberian plates. Deep seismic reflection profiling across the North Qilian Moutnains yielded the evidence that the Kuantanshan fault plunged beneath the Qilian Mountains, which has been also by many deep-seated geophysical data such as the deep velocity structure and deep temperature structure (Figs. 3 and 4 in Gao et al., 1995). We consider the fault to be a "boundary fault" on the northern margin of the plateau and call it the "north boundary thrust" (NBT) (Li, 1995; Gao et al., 1999). It coincides with the northern boundary of the Qinghai-Tibet seismically active belt. The stress field determined by the seismic mechanism also indicates that the Qinghai-Tibet Plateau was in a state of bidirectional compression.

Under the bidirectional compression, the upper crustal slices were thrust and overlapped each other along the detachments and the rocks underwent brittle deformation, thus leading to shortening and thickening of the upper crust. The fact that numerous earthquakes of the plateau happened at depth above 33 km may indicate the depth of the brittle–semi-brittle deformation, too. Compression also brought about strong deformation on the top of the upper mantle, thus giving rise to imbricate overlapping of the Moho and bidirectional (upward and downward) thickening of the crust (Gao, 1990). The local displacement of the Moho caused the lower crust to be detached from the upper mantle; as a result, the cold heavy lithsopheric mantle sank and the hot, light asthenospheric mantle rose, thus causing local melting. The second low-velocity, high-conductivity layer of the lower crust in northern Tibet might be formed just by such local melting. The hot buoyant effect produced by upwelling of asthenopheric material might be one of the causes for the rapid uplift of the plateau and meanwhile promoted the extension of the upper part of the crust (Gao and Wu, 1995). The high-K volcanic rocks in the Qiangtang area, northern Tibet, might have been formed in this dynamic setting.

Geophysical surveys have revealed the convergence relations of various terranes. The deep configuration of the terrane boundaries may not only reflect the signs of collage and suturing of various terranes but also show the modified features. The terrane boundaries (ancient suture zones) slipped laterally along the strike under the compression, resulting in relatively great undulation of the Moho on both sides. This suggests that the depth affected by the strike slip might be very great (Gao et al., 1990).

To sum up, the unstable change of the Moho, the interaction between the crust and mantle and between the lithosphere and asthenosphere cuased by the sinking of the lithospheric mantle and the strike slip and extension of the crust are the major dynamic factors for maintaining the present height and extent of the Qinghai-Tibet Plateau.

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