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Tectonic evolution and uplift of the Qinghai–Tibet Plateau

Based on a paper presented at the 10th Himalaya–Karakoram–Tibet Workshop, Ascona, Switzerland, 1995

Recent studies on palaeobiogeography, sedimentography and palaeomagnetism, show that terranes comprising the Qinghai–Tibet plateau and accreting to Eurasia during the late Palaeozoic–Mesozoic, did not drift northward across a vast ocean. At that time there was only an epeiric sea, or a limited ocean basin, rather than a vast eastward-opening Tethys. Uplift rates of the plateau have been deduced and a mechanism for the formation of the plateau is described.

Tectonic evolution

The tectonic evolution of the Qinghai–Tibet plateau (QTP) is related to the splitting of Gondwana land and to the evolution of Tethys. It is one of the highest plateaus in the world, an active earthquake zone, a strongly uplifted mountain region and a place of unique morphogenesis making it an area of considerable interest and the subject of lively discussion among geoscientists worldwide.

The tectonic units of the Qinghai–Tibet plateau and the suture zones between them are shown in Figure 1.

Figure 1 Tectonic divisions of the Qinghai–Tibet plateau and adjacent areas. I Indian craton (terrane); II Himalaya terrane; III Gangdise (or Lhasa) terrane; IV Qiangtang terrane; V Hohxil–Baryan Har terrane; MBT main boundary fault zone; YTSZ Yarlung–Tsangpo suture zone; LBSZ Lancang–Bangong suture zone JSZ Jinshajiang suture zone.

Table 1 Tertiary palaeomagnetism and crustal shortening of the Qinghai–Tibet plateau.

Terrane	Age	Palaeolatitude (D°)	Modern latitude (D ₁ °)	Northward displacement & latitude (D ₁ °–D°) × 110	Distance between terranes	Shortening of crust (km)	Source of data
Himalaya	Tertiary	4.5° N (2.5°–5°, 4.6° N)	28.5° N	24° 2664 km			A
Gangdise	Tertiary	12° N (10–13.8)	30° N	18° 1980 km	130 km	2664 – (1980+130) = 554	B
Qiangtang	Tertiary	27.5° N (25.4–29.5)	32.5° N	5° 550 km	440 km	1980 – (550+440) = 990	C
Qaidam	Tertiary	37° N (34°–40°)	38° N+	1° 110 km	480 km	550 – (110+480) = –40	D

A Sino-French joint investigation in Himalaya region, 1984, Dong Xuebing et al., 1990.

B Michele Westphal, Zhou Yaoxin et al., 1983, Dong Xuebing, 1990.

C Zhou Yaoxin, Courtillot, et al., 1984, Dong Xuebing, 1990.

D Dong Xuebing, 1992, Li Yongan, 1992.

Since the emergence of plate tectonic theory in the late 1960s, many geoscientists have believed that the Indian terrane, the Himalaya terrane and the southern terranes of the Qinghai–Tibet plateau successively accreted to Eurasia, after being separated from northern Gondwana land, and drifting northward across a vast deep ocean 7000–8000 km wide, the so-called palaeo-Tethys, around 200 Ma ago (Dietz and Holden, 1970).

Recent studies on palaeobiogeography, sedimentary facies and palaeomagnetism indicate that during the late Palaeozoic–early Mesozoic (Triassic), most of Tethys was an epeiric sea instead of a vast deep ocean, except perhaps for belts along the Jinshajiang River and the South Kunlun Mountains. These might have been rifted to form a narrow deep trough or a small ocean basin represented by minor and dismembered ophiolite. A quantitative palaeobiogeographical analysis of the Carboniferous–Triassic fauna and flora of Qinghai–Tibet has been presented by Smith et al. (1990). It indicates that there was no suture line consistently marking the position of a faunal or floral break during the late Palaeozoic–late Triassic and there appears to have been no physical barrier, such as a vast ocean, to biotic dispersal between terranes of the Qinghai–Tibet plateau at that time. A palaeomagnetic study also indicates that in the late Palaeozoic, there was no 7000 km-wide ocean between Eurasia and Gondwana from which a number of blocks became detached, including south China, Indochina, Afghanistan, Iran, Kunlun, Qiangtang and Karakoram etc., and accreted to form the Cathaysian composite continent (Lin Jinlu et al., 1990).

Tetrapod fossil evidence (Chatterjee, 1987; Sun Ailing et al., 1992) shows that all of the Indian Tetrapod families are present in the northern region including China, East Asia, Africa, Europe and particularly North America but are absent in Australia and Antarctica. So it is believed that the India plate and Asia remained an integral geographic unit during the late Triassic and even early Jurassic. In the Jurassic to early Cretaceous period, although the Yarlung–Tsangpo suture zone seems to be the result of the closing of an ocean basin, the palaeobiocoenosis, palaeogeography and sedimentary facies both to the north and south of the Yarlung–Tsangpo suture zone were characterized by an epibenthic environment (Xia Daixiang et al., 1993). Therefore, the ophiolite occurring along the Yarlung–Tsangpo suture zone probably represents relics of oceanic crust–upper mantle rocks of a limited (small) ocean basin or a narrow deep trough of Jurassic to early Cretaceous age.

The REE, bulk composition, stable elements and isotope contents of ophiolites can be used to deduce (even if indirectly) the spreading rate parameters. Such data from the Yarlung–Tsangpo ophiolite suggest a slow spreading rate (less than 2 cm/a, averaging about 1.5 cm/a) (Mo Xuanxue, 1992; Xiao Xuchang, in press). The duration of the ocean basin represented by the Yarlung Tsangpo

ophiolite is from about 190 Ma (Jurassic) to 100 Ma (early Cretaceous). The width of the basin is roughly estimated at 2700 km [$(190–100)\text{Ma} \times 1.5\text{cm/a} \times 2$].

All of the above evidence indicates that the Indian terrane lay near the Gangdise (Lhasa) terrane and did not drift far to the south. From the Jurassic to the Cretaceous, most of the area between the Indian terrane and the QTP was covered by an epeiric sea. The Yarlung–Tsangpo suture zone resulted only from the subduction and consumption of a limited (small) ocean basin. During that time, Antarctica and Australia split from India, and drifted to the south.

It is appropriate to recall the words of Alfred Wegener (1924), written 60 years ago, on the evolution of the Himalayas and Tibetan high land:

The case of India is somewhat different: it was originally connected by a long continental tract, mostly, it is sure, covered by shallow sea, to the Asiatic continent... this long connecting portion was more and more folded together through the continuous gradual approach of India to Asia and constitutes today the mightiest mountain folds of the earth, the Himalayas and the numerous folded ranges of the highlands of Asia.

Crustal thickening, shortening and uplift

From studies of palaeomagnetism, sedimentology, tectonic history, stratigraphic palaeontology, magmatism, high-pressure and low-temperature metamorphic belts and ophiolite, the unanimous view is that the neo-Tethys ocean basin closed at the end of the Cretaceous–Eocene, and the Indian terrane collided with Eurasia; since then (about 65–50 Ma ago), there has been crustal thickening, shortening and uplift in the QTP.

Until now, estimates of the rate of northward movement and displacement of the Indian terrane since the Tertiary have not been generally accepted, but some idea of the rate is possible after preliminary analysis. The main conclusions of this analysis are:

- The northward drift rates of the Indian terrane after its convergence with Eurasia in Eocene epoch was 16–17 cm/a at 65–50 Ma; about 10 cm/a in the Oligocene–Miocene, and 2–10 cm/a in the late Pliocene (Dong Xuebin et al., 1990; Klootwijk et al., 1992; Molnar et al., 1987; Patriat et al., 1984; Zhou Yaoxin et al., 1990). The accepted rate of the northward compression from the Indian terrane since the Pliocene is 50–60 mm/a, of which 5 mm/a is absorbed by compressive faults or thrusts in the Himalaya terrane; 15 mm/a by the strike-slip faults in the Gangdise terrane; 12 mm/a by the strike-slip faults in the Qiangtang terrane; 8 mm/a by the strike-slip faults

Table 2 Tertiary uplift rates of the Qinghai–Tibet plateau.

Method	Region (from S to N)	Uplift age	Uplift rate (mm/a)	Denudation rate (mm/a)	Source of data
Geodetic levelling GPS+ SLR	1 Qomolangma (Everest)	last 30 years	37		J Y Chen et al. (National Bureau of Surveying and Mapping, China, 1994)
	2 Himalaya	0.01 Ma–last few years	10–15		
	3 Lhasa–Gangdise	0.01 Ma–last few years	9–10		
	4 Kunlun–Karakoram	last 30 years	6–9		
Fission track	Western Himalaya	5–1 Ma	0.2–0.9	5 (?)	P K Zeitter et al., 1985, 1991
		20–10 Ma	0.92	0.08–0.22	
		40–30 Ma	0.1–0.3		P F Cervený et al., 1988
	Lhasa–Gangdise	12–8 Ma	0.45–0.5 0.25		Liu Shunsheng et al. (Institute of Geology Academica Sinica)
Study of dislocation geomorphology	Karakoram	0.01 Ma–last few years	4–5		Liu Qing (Doctoral thesis 7th University of Paris, 1993)

and the Red River right lateral strike-slip fault in the Yunnan block; about 11 mm/a by the Altun, Kunlun and Qilian fault systems, and about 3–5 mm/a by the Tianshan fault system.

- From the Himalaya Lhasa to Qaidam terrane, the displacement successively decreases, i.e. from 2664 km to 110 km (Table 1).
- It is noteworthy that, based on the movement distance of the above terranes, the crust shortening (or compression) from the Gangdise terrane to Qiangtang terrane can be roughly calculated, at 990 km. This is more than the shortening between the Himalaya and Gandise terranes or that between the Qiantang and Qaidam terranes. These data are consistent with those of the geophysical survey, i.e., the Gangdise terrane and the area north of it have a 'thick crust', also indicating that the Qaidam terrane in the north of the QTP was an obstruction to the compressive force from the south.

The rapid uplift of the QTP since the late Tertiary is fully demonstrated by data on neotectonics, geomorphology, palaeontology and sedimentology (Li Tingdong, 1988; Pan Guitang et al., 1990; Zhang Qingrong et al., 1992). The uplift rates of the QTP, obtained using various methods in the last few years, are generalized in Table 2. The rate of uplift has increased with time: 0.1–0.4 mm/a in the Eocene to Miocene, 0.4–0.5 mm/a in the Pliocene to Pleistocene, and 4–15 mm/a in the Pleistocene to Holocene. Since the Holocene, the uplift rate has increased rapidly from north to south (Figure 2).

The uplift process of the QTP can be divided into three major stages:

- A slow uplift stage in the late Cretaceous–Eocene, which mainly resulted from the collision between the Indian terrane and the southern terrane of the QTP as well as the subduction of the former beneath the latter.
- A medium uplift stage in the Oligocene–Pliocene, which mainly resulted from the compressive deformation within the amalgamated terranes.
- A rapid uplift stage in the Holocene, which mainly resulted from the isostatic adjustment.

Concerning the uplift model and mechanism, there have been lively discussions during the last 20 years. (Dewey, Shackleton, Chang Chenfa and Sun Yiyin, 1990; Harrison et al., 1992; Li Tingdong, 1988; Meng Lingshun, 1992; Molnar et al., 1987a; Patriat et al., 1984; Pan Guitang et al., 1990; Shen Xiangjie et al., 1992; Stocklin, 1983; Tapponnier et al., 1986; Teng Jiwen, 1985; Research Group of the CIT, Harvard Univ. and MIT, 1987; Regional Geology of Tibet, 1993; State Seismological Bureau, 1992). Space limitations prevent all of the diverse models that have been proposed to be pre-

sented one by one. Many factors have contributed to the thickening, shortening and uplift of the QTP and among these, the following should be taken into consideration in the model:

- 1 Tectonic deformation is the main factor. Geophysical data obtained in the last ten years reveal that the QTP, and may be divided into three structural layers. The first layer, considered as the upper crust, extends to 10 to 30 km. Brittle and ductile deformation are dominant in this layer. A low-velocity/low-resistivity layer at the base of the first layer (Xiao Xuchang et al., 1988) acts as a decoupling level along which listric thrusting caused crustal thickening, shortening, and uplift of the plateau. The second structural layer, regarded as the lower crust, is between the low-velocity/low-resistivity layer and a depth of 50–60 km. Here the crustal thickening and shortening was induced mainly by ductile and plastic deformation. The third structural layer is at a depth of 50–60 to 70–80 km, and is characterized by anomalous mantle or crust–mantle mixtures due to the upwelling of mantle materials and their interaction with the crust. This layer is dominated by plastic deformation which caused the crustal thickening and shortening.

Figure 2 Diagram showing the uplift rates of the Qinghai–Tibet plateau during the Tertiary.

Heat flow, hydrothermal activity and melting are the important factors which cannot be neglected when considering the tectonic history of the QTP:

- Heat flow of about 71 mW/m² has been measured to the south of the QTP in Katmandu, Nepal, and to the north of this, in the Qaidam basin it is about 70 mW/m². In the plateau proper however the heat flow increases to 92 ~ 146 mW/m² (Shen Xiangjie et al., 1992).
- Very low Q values prevail in the QTP. Q_B is 65~100 at a depth of 13~33 km in the upper crust and 18~110 at 55 km in the lower crust. These values are most probably consistent with the upper and lower low-velocity layers respectively (Teng Jiwen, 1985).
- Long-period seismic records show that the Lg phase is weak or missing in the QTP.
- The results of tomographic studies show that a swell (plume?) exists at depth, reaching the core-mantle boundary beneath the QTP. This also suggests that the heat flow energy is from a very deep layer (Research Group of the CIT, Harvard Univ. and MIT, 1987).

The deep geophysical data, the heat flow, the seismic velocity data, the very low Q values, the missing Lg wave and the seismic tomography seem to indicate that there is a low-viscosity, highly molten layer with intense geothermal activity in the deeper part of the QTP. The thickening, shortening and uplifting of the QTP were probably brought about by heat expansion.

Isostatic adjustment is one of the major factors in the last stage of uplift of the QTP. Since the Tertiary, lithosphere downwarping inevitably has occurred due to the static load pressure resulting from the thickening of the crust. So the QTP was in the state of isostatic compensation. Later, in the Pleistocene to Holocene, the compressive force from the Indian terrane decreased, leading to upwarp of the previously downwarped area.

Rapid uplift and high positive gravity isostatic anomalies (60~803 10⁻⁵ m/s²) occurring in the Himalaya region since the Tertiary (Meng Lingshun, 1992) are due to intensive compressive stress and strong deformation events such as the thrusting, over-faulting and overlapping. These affected both the lithosphere and upper mantle and resulted in the upper mantle being squeezed upwards. To the north of the Himalaya region, the compressive stress was released and isostatic adjustment led to the uplifting of the Tibet plateau.

Conclusions

Multidisciplinary studies indicate that during the late Palaeozoic to early Mesozoic, most of Tethys was an epeiric sea, not a vast deep ocean. The presence of ophiolites and ophiolitic melanges along the Yarlung-Tsangpo (YTSZ), Lancang-Bangong (LBSZ) and Jinshajiang (JSZ) suture zones fully demonstrate that a narrow deep trough or a small oceanic basin, was formed by rifting.

The causes of the rise of the Qinghai-Tibet plateau are complicated, involving many factors. Our preliminary synthesis indicates that early-stage compression by the India terrane; thermal effects and expansion; and a late-stage (Pliocene to Holocene) isostatic adjustment are the three major factors leading to the rise of the plateau.

Acknowledgments

The authors deeply thank Professors J Y Chen, S Chatterjee, Li Tingdong, Lin Jinlu, Meng Lingshun, A B Smith, Shen Xianjie, Wen Shizuan, D R Watts, Xu Juntao, and Yang Jingsu as well as others for providing papers concerning the tectonic evolution and the rise of the Qinghai-Tibet plateau.

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