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Continental subductions and Tibetan plateau growth

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ABSTRACT

How and when the Tibetan plateau developed has long been a puzzling question with implications for the current understanding of the behaviour of the continental lithosphere in convergent zones. We present and discuss recent data acquired in geology and geophysics and through igneous and metamorphic petrology and palaeo-altitude estimates. This research indicates that Tibet initiated from the accretion of the Gondwana continental blocks to the southern Asian margin during the Palaeozoic and Mesozoic eras. These successive accretions have potentially favoured the creation of local landforms, particularly in southern Tibet, no evidence exists in favour of the existence of a proto-Tibetan plateau prior to the Cenozoic. By the time the India-Asian collision began it was cold enough to transfer stress but that does not mean there was not a proto-plateau prior to collision. Depending on the types of Paleozoic and Mesozoic collisions, the sutures terranes could be cool enough to transfer stress, especially in the upper crust. However, these successive accretions associated with subductions have metasomatized the Tibetan lithospheric mantle and largely explain the potassium- and sodium-rich Cenozoic magmatism. Another consequence of this contamination by fluids is the softening of the Tibetan lithosphere, which favoured intra-continental subductions. The timing and the geochemical signatures of the magmatism and the palaeo-altitudes suggest the early growth of the Tibetan plateau. By Eocene time, the southern plateau and the northern portion of Himalaya were at an altitude of approximately 4000 metres, while the central and northern Tibetan plateau was at altitudes of approximately 2000 to 3000 meters at the Eocene-Oligocene transition. From all of these data, we propose a model of the formation of the Tibetan plateau coupled with the formation of Himalaya, which accounts for more than 2500 km of convergence accommodated by the deformation of the continental lithosphere.

Key words: Continental subduction, tectonics, magamtism, geophysics, Tibetan Plateau

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GEOLOGICAL AND GEOPHYSICAL SETTING

The Himalaya-Tibet orogenic system, expanding from the India in the south to the North China block in the north (Fig. 1), is a result of the India-Asia collision. Before the collision, Tibet was built by successive accretion from north to south of microcontinents detached from Gondwana and accreted to the southern margin of Eurasia from the early Palaeozoic to the Mesozoic. From north to south, a minimum of 6 younging-southward sutures can be identified (Yin and Harrison 2000). Whether these previous collisions participated in the thickening of the Tibetan crust is a difficult question to answer. With the exception of the south Lhasa terrane, which have resembled the present-day Andean active margin during Cretaceous time, that is with local reliefs (Kapp et al. 2007), the Tibetan plateau is covered with Cretaceous and Palaeocene red bed sediments, suggesting that the major part of the Tibetan crust had a normal thickness. Therefore, we assume that most of the thickening of the Tibetan crust is due to the India-Asia collision. According to the tectonic upper-crustal reconstruction, a minimum of 800 km of north-south shortening is estimated throughout Tibet (Yin and Harrison 2000).

As extrusion possibly accommodated up to 30% of the convergence along the major strike-slip faults (Replumaz and Tapponnier 2003), the total shortening accommodated within the Tibetan plateau, including the eastward extrusion, is a minimum of 1000 km in length (Table 1). The crustal mass budget shows that only 3% of the Tibetan crust was recycled into the mantle, suggesting that the entire crust was stored in the Tibetan plateau and participated in its thickening (Replumaz et al. 2010).

Increasingly accurate geophysical data shows that the Moho beneath Tibet is not as flat as previously thought (Fig.

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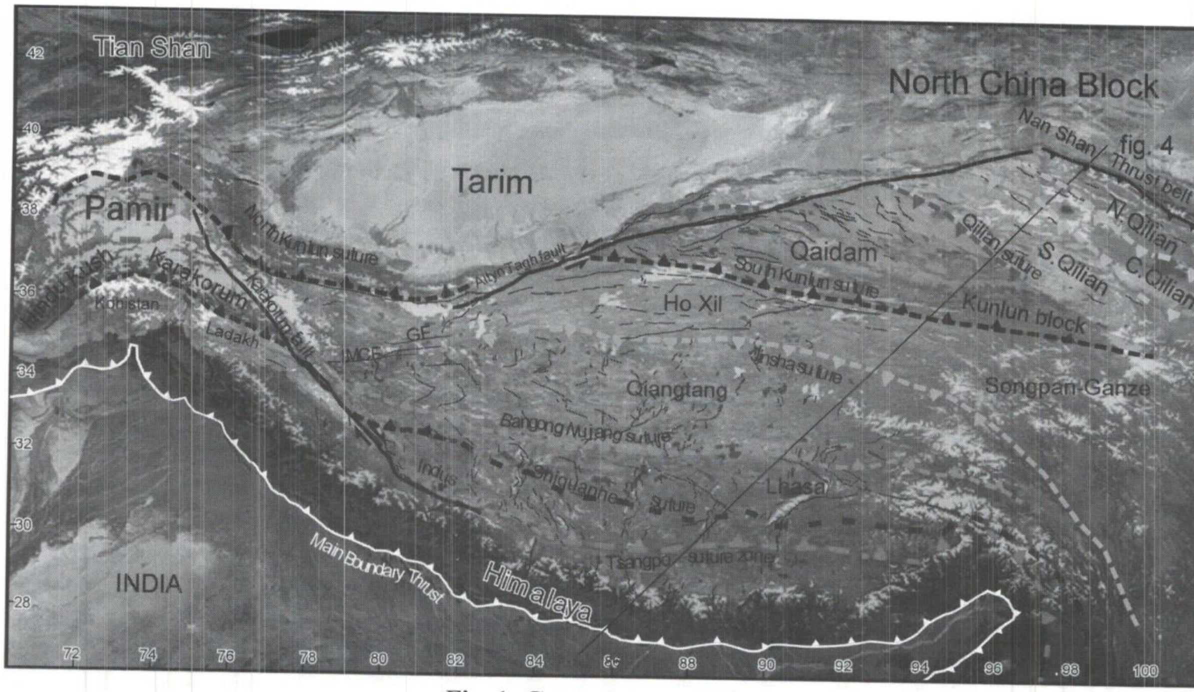

Fig. 1: General map of Tibet.

2). The south Tibetan crust is thick up to 80 km and this thickness is related to the underthrusting of the Indian lower crust Nabelek et al., 2009. Deep seismology also images the Indian lithospheric slab subducting beneath southern Tibet. Beneath the Qiangtang and Songpan Ganze terranes, the Moho depth is approximately 70 km, decreasing abruptly up to 50-55 km beneath the Qaidam basin (Karplus et al. 2011). Central Tibet is characterised by a relatively thin lithospheric root ~110 km. To the north, the Moho depth increases to 75 km and is related to the southward subduction of the north China block. Moreover, another tomographic anomaly, As, is observed at 900-1000 km of depth beneath the Lhasa terrane (Fig. 2). This anomaly is interpreted as a remnant of the Songpan-Ganze slab subducted beneath the Qiangtang terrane approximately 40 Ma ago (Replumaz et al. 2010).

Cenozoic magmatism and the associated xenoliths are widespread in Tibet. This magmatism is dominated by ultrapotassic and $Na_2$0-rich calc-alkaline lavas symptomatic of the melting of a metasomatised lithospheric mantle or asthenospheric mantle with a lower crustal contribution in the context of a heat source supply (Chung et al. 2005; Ding et al. 2007). The melting of the lower Tibetan crust is highly debated, as its occurrence may have controlled the potential existence of the lower crustal channel flow with a low viscosity of 1017 to 1018 Pa.s. Xenoliths of the lower crustal rocks collected by Tertiary lavas show that the lower crust beneath Tibet records temperatures greater than 850°C, and most of them represent the dry residue of lower-crustal melting (Hacker et al. 2005). Under these thermal and petrological conditions, the viscosity of dry residue granulites should increase to a minimum of 1021 Pa.s (Labrousse et al. 2010), rather than 1018 Pa.s. Based on their numerical experiments, Copley et al. 2011 also proposed

Table 1: Estimations of tectonic shortening in Himalaya, Tibet and along the major faults (Guillot and Replumaz 2012).

Shortening	Himalaya	Tibet					Major Faults		
		Lhasa	Qiangtang	Songpan-Ganze	Qaidam	Qilian & Nan Shan	Karako-rum	Red River	Altyn Tagh
Eocene	600±200 km				~110 km	80±20 km			
Post-Eocene	900±100 km	>110 km	>40 km	>150 km	~60 km	~270 km	300-400 km	700±200 km	280-550 km

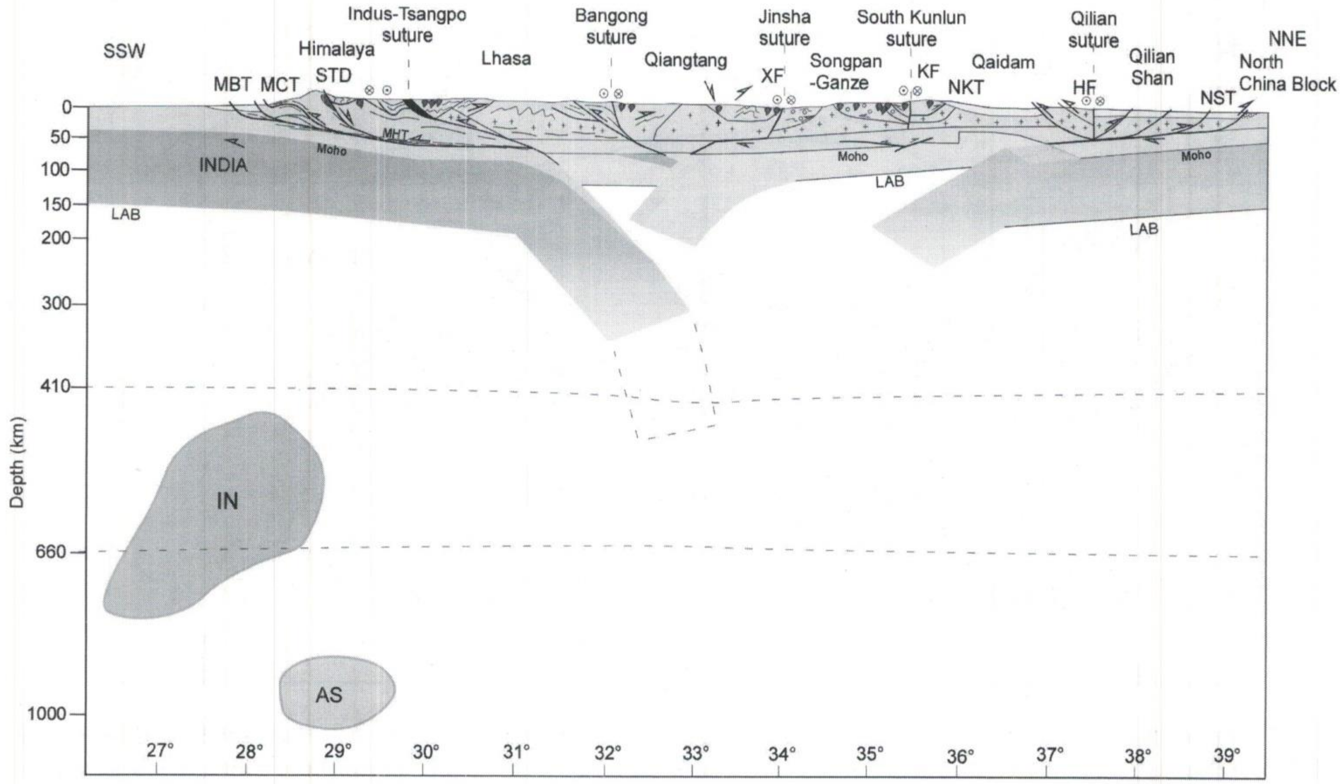

Fig. 2: Interpretative cross-section of the Himalaya-Tibet orogenic system at the mantle scale (from Guillot and Replumaz 2013).

that the Indian lower crust is strong with a viscosity $> 5\times10^{23}$ Pa.s, which is $> \sim 10^2$ times higher than the upper limit of the viscosity of southern Tibet predicted in a prior modelling by (Clark and Royden 2000).

This point questions the present rheological state of the lower crust beneath Tibet. Low-velocity zones 'bright spots' imaged by the INDEPTH seismic experiment in southern Tibet have extensively been interpreted as widespread partial melt within the mid-crust, which has provided strong support for the channel flow model (Beaumont et al. 2004). These data suggest that a continuous seismic low-velocity zone underlies Tibet on a large scale. However, Hetenyi et al. (2011) have shown that the vertical extension of the low-velocity zones is only 10 km in length, and their maximum horizontal length appears to be approximately 50 km. These researchers' study suggests a partial correlation between the location of these low-velocity zones and the spatial distribution of Tibetan grabens where Quaternary volcanism is observed. Therefore, we can conclude that at present, the lower Tibetan crust is mostly hot and dry, while the mid-crust is locally affected by partial melting.

PAST PROPERTIES AND CENOZOIC EVOLUTION

In south Tibet, the Linzizong volcanism 65-40 Ma marked the transition from oceanic to continental subduction , while the post-40 Ma volcanism records the onset of the thickening of the Lhasa crust (Guo et al. 2012) (Fig. 3). This early thickening of south Tibet is compatible with recent thermochronological data indicating that, by 35-40 Ma, the southern Tibetan plateau was already high in elevation and slowly uplift since then (van der Beek et al. 2009; Hetzel et al. 2011; Rohrmann et al. 2011).

The Palaeocene to Eocene volcanism in the southern and northern Qiangtang terrane (Fig. 3) recorded the northward subduction of the Lhasa terrane and the southward subduction of the Songpan-Ganze terrane, respectively (Ding et al. 2007). Geophysical evidences of central Tibet subductions are scarce; the Moho steps along the Bangong and Jinsha sutures and the AS tomographic anomaly (Fig. 2) provide scarce evidences. These northern and southern continental subductions were probably responsible for the

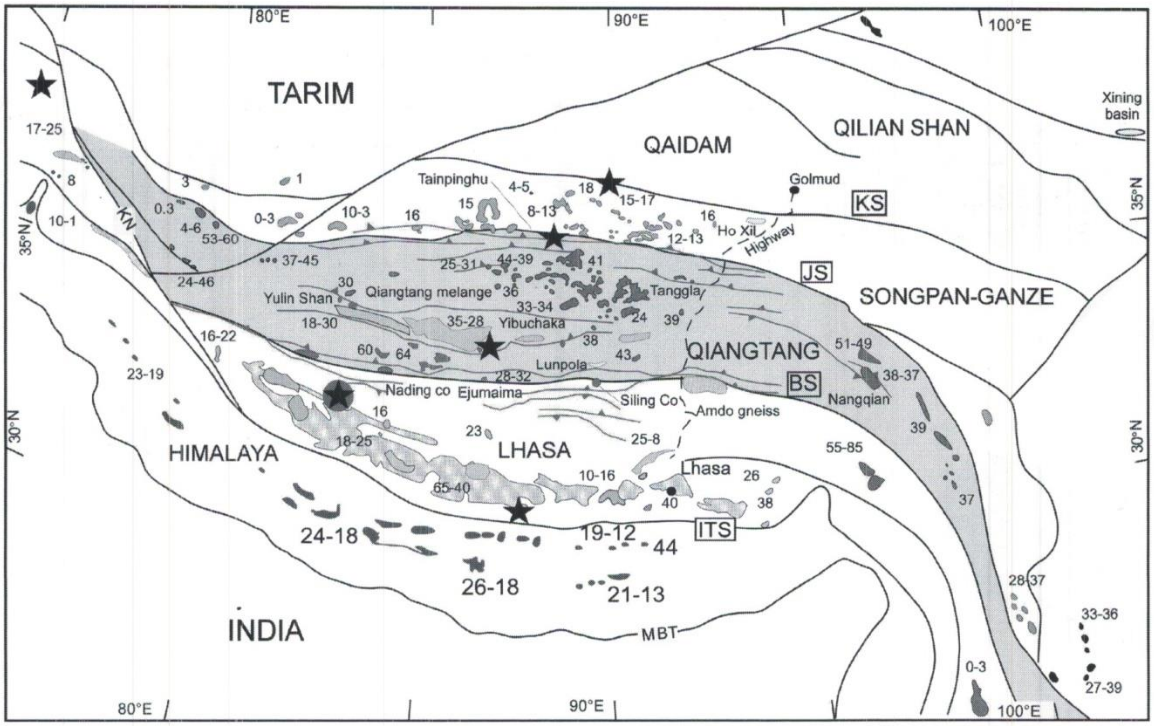

Fig. 3: Map of the Tibetan plateau showing Cenozoic magmatism modified from Chung et al. (2005) and Ding et al. (2007), including xenolith localities black stars, modified from Chan et al. (2009). In southern Tibet, the large shaded area corresponds to the Palaeogene Linzizong volcanic province. Abbreviations: BS—Bangong suture; ITS—Indus–Yarlung suture; JS—Jinsha suture; KS—Kunlun suture.

thickening and uplift of central Tibet, as has been shown that the Lunpola basin in central Tibet has been elevated 4000 m since the late Eocene period (Rowley and Currie 2006). The Neogene magmatism in south Tibet and Karakorum is symptomatic of a second slab break-off of the Indian continental slab, while the Neogene north Tibetan magmatism active since 15 Ma is interpreted as melting of the lower crust or the uppermost lithsopheric mantle caused by a heat supply (Mahéo et al. 2002). It is notable that beneath the Neogene north Tibetan magmatism province, the Asian slab is not coupled with the Tibetan Moho, and the crust beneath the Qaidam basin is thinner (Fig. 2). Karplus et al. (2011) proposed that this peculiar geometry is related to the underthrusting or northward flow of the Songpan-Ganze lower crust beneath the Qaidam Moho. We favour another solution: the continuous southward subduction of the north China block beneath the Qaidam basin since the beginning of the India Asia collision followed by a slab retreat since 15 Ma, enhancing the formation of the Neogene north Tibetan magmatic province.

The initial Tibetan lithosphere had to be weak enough to be thickened by homogeneous thickening. However, in the general context of continental subduction, another possibility is that solely the Tibetan lithospheric mantle was weak, which facilitates the subduction of the strong Indian and Asian lithospheres on both sides of Tibet while the crust was strong enough to localized the deformation. Rey et al. (2010) modeled the formation of plateau, showing that the production of an elevated plateau 5000 m 10 to 15 m.y. after the beginning of the convergence required an initial Moho temperature of approximately 560°C. Therefore, a cold and consequently initially rigid crust is required to instantaneously transmit the Indian horizontal forces to the north, initiating the Palaeocene-Eocene southward subduction at the southern edge of the north China craton and the development of long-lasting strike-slip faults. This model favours the idea that the initial Tibetan crust was already cold and consequently rigid. In contrast, a requirement for the development of a wide plateau is the presence of weak regions (Whitney et al. 2009). This weak region can correspond to the initial Tibetan lithospheric mantle sandwiched between the cold and strong Indian lid in the south and the Asian one in the north. The negative P-wave velocity beneath central Tibet is usually interpreted as being related to a thin lithospheric mantle delaminated and replaced by a hot asthenosphere between 10 and 20 Ma ago, leading to the general uplift of the Tibetan plateau (Molnar et al. 1993). However, there is no evidence of widespread magmatism at that time (Ding et al. 2003). Feng et al. (2011) proposed that the 110 km thickness of the lithosphere beneath Tibet is normal and corresponds to the initial lithosphere of the accreted terranes from the Palaeozoic to Mesozoic periods. The relatively lower velocity of the Tibetan mantle could be related either to hotter temperature or to the presence of hydrated minerals reducing the viscosity of the lithosphere to the viscosity of the asthenosphere. This latter interpretation is compatible with the geochemical signature of the Cenozoic magmatism (Ding et al. 2007), suggesting that the Tibetan mantle was previously metasomatised before melting (Fig. 4).

A GENETIC MODEL FOR THE TIBETAN PLATEAU FORMATION

Therefore, we propose that three main factors concurred in the Eocene-oligocene growth of a 1000 km wide Tibetan plateau:

1. The occurrence of cold and strong continental cratonic lithospheres north and south of the Palaeozoic- to Mesozoic-accreted terranes. These cratonic lithospheres partly subduct, but they also play the role of indenters.

2. A "normal" initial Tibetan crust constituted by the amalgamation of continental terranes and arc-related crustal products, with only local topography. This initial crust was cold and rigid enough to transmit instantaneously the horizontal forces from the Indian plate to the Asian plate.

3. An initial soft Tibetan lithosphere, sandwiched between cratonic lithospheres, which facilitates their subduction. The thickening of the Tibetan crust was probably accommodated by three or four complementary mechanisms: nappe stacking in the upper crustal levels, as observed along the Sinquanhe-Gaize-Amdo thrust in southern Tibet (Kapp et al. 2007) or in the Qilian shan (Tapponnier et al. 1990), the underthrusting of Indian or Asian lower crustal materials at the Moho level participating in the thickening of the lower Tibetan crust (Nabelek et al., 2009). Mantle-derived magma was underplated at the base of the Tibetan Moho or transferred at the upper-crustal level. Magmatism is discontinuous in space and time in Tibet and is mostly controlled by a period of asthenospheric heat supply during slab break-off processes ~45 Ma and 25-15 Ma for India, 45-33 Ma for Asia (Guillot and Replumaz 2013). During these peculiar periods, the Tibetan crust was partly molten at the scale of the magmatic province, which enhanced the local crustal flow and the local homogeneous thickening. A secondary effect of the partial melting of the Tibetan crust is its progressive granulitisation and its consequent rigidification. Therefore, we propose that episodic periods of magmatism and subsequent granulitisation in different

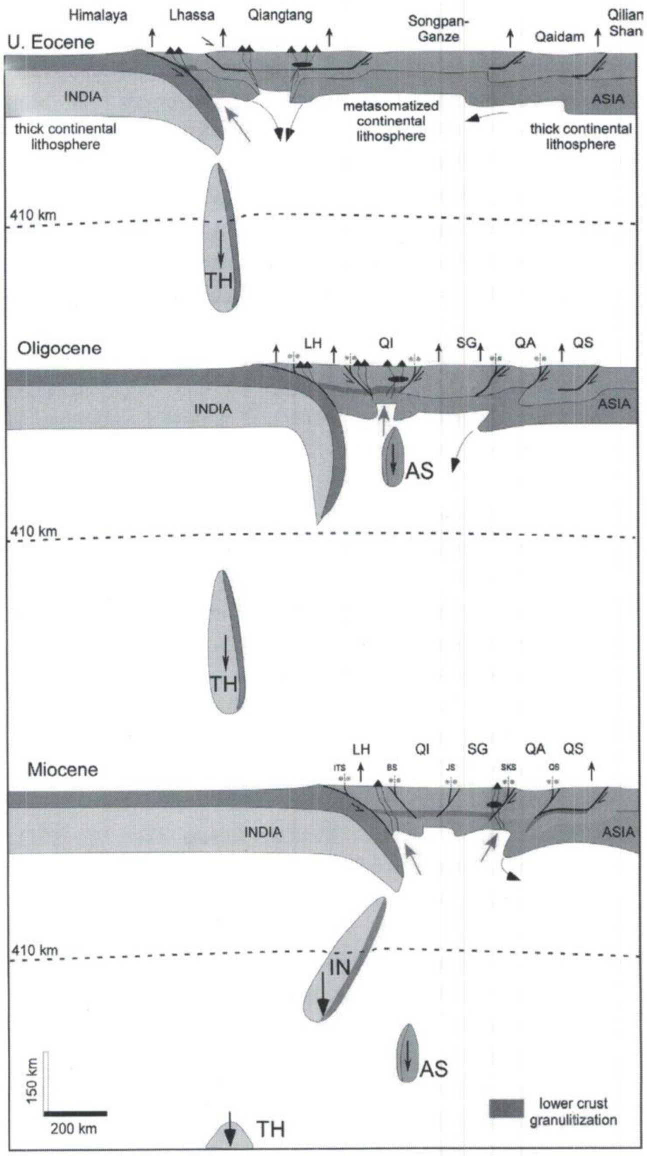

Fig. 4: Proposed evolution of the Himalaya-Tibet orogenic system at the lithospheric scale. This model takes the tomographic and geophysical data into account, as well as the tectono-metamorphic and magmatic evolution and the estimates of the shortening discussed in the text (modified from Guillot and Replumaz 2013).

Tibetan areas provoked hardening of the lower crust.

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