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# India-Eurasian collision *vs*. ocean-continent collision*

ZENG Rong-sheng[1),♣] (曾融生) WU Qing-ju[1)] (吴庆举) DING Zhi-feng[1)] (丁志峰)
ZHU Lu-pei[2)] (朱露培)

1) *Institute of Geophysics*, *China Earthquake Administration*, *Beijing* 100081, *China*
2) *Department of Earth and Atmospheric Science*, *Saint Louis University*, *Missouri* 63103, *USA*

**Abstract**

Ample observational evidence shows that there is a northward crustal subduction zone underneath the Yarlung Zangbo suture between India and Eurasia. It penetrates Moho to a depth of about 100 km. There are probably multiple such crustal subductions under the Himalayas. They are different from lithosphere subduction during oceanic collisions. The detected slabs in the upper mantle north of the Yarlung Zangbo suture can be interpreted as remains of the Indian Plate's mantle lithosphere. In contrary to ocean-continent subduction, the mantle lithosphere is delaminated from the crust as the Indian Plate subducts underneath Eurasia. Existing structural images of the crust and upper mantle of the Tibetan Plateau reveal that there were both northward and southward subductions over different geological periods, causing some seismic velocity anomalies around those subduction zones.

**Key words**: **India-Eurasian collision**; **ocean-continental collision**; **delamination**
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## Introduction

Major tectonic activities occur in collisions zones between plates or intra-plate continental blocks. Therefore, it is significant to investigate collision processes. We know that orogenic and seismic belts in plate margins are closely related to ocean-continent collision. Similarly, the rise of the Himalayan mountain range and the Tibetan Plateau, the large-scale strike-slip faults and rifts in western China, and the seismicity in the interior of Chinese mainland are directly linked to the India-Eurasian continent-continent collision.

Collision processes of ocean-ocean or ocean-continent plates were understood in the 1960s (Lsacks *et al*, 1968). In case of ocean-continent collision, it is the whole oceanic lithosphere subducting beneath the continent from the results of earthquake hypocenter locations and upper mantle structure (Figure 1). The maximum depth of the subducting slab varies from place to place, and can be several hundred kilometers deep or even deeper than the 670-km-discontinuity (Van der Hilst *et al*, 1997).

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**Contribution No**.07FFE3001, Institute of Geophysics, China Earthquake Administration.
♣ **Author for correspondence**: zengrs@public.bta.net.cn

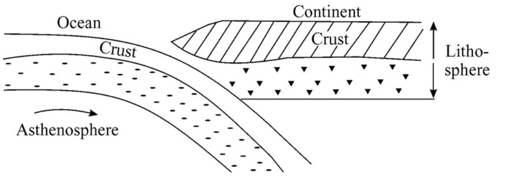


Figure 1 Cartoon showing the ocean-continent collision process

The collision process between continents is not clear so far. Because of the on-going collision of the India continental plate with Eurasia, the Himalaya and Tibetan Plateau have been considered a natural laboratory to test theories of the continent-continent collision process.

There were many models proposed regarding the India-Eurasian collision, which have been summarized by some authors (Dewey *et al*, 1988; Willett *et al*, 1993; Yin and Harrison, 2000). However, many previous models lack sufficient supporting observations. In general, continent-continent collision models can be divided into two categories. One category of the models suggests that lateral flow underneath asthenosphere produces horizontal compression in the lithosphere which causes deformation near the suture zone and in the continent interior accompanied by strong magmatic and seismic activities (England and Houseman, 1986; Houseman and England, 1996; Tapponnier and Molnar, 1997). The other category of models believes that the process is similar to that of ocean-continent collision in which the active plate subducts beneath the passive plate (Seeber *et al*, 1981; Barazangi and Ni, 1982, 1984; Mattauer, 1986; Beghoul *et al*, 1993; Matte *et al*, 1997; Owens and Zandt, 1997; Tapponnier *et al*, 2001). These two categories of models interpret continental geology and tectonics differently. With the accumulation of reliable geophysical results on the Himalaya and the Tibetan Plateau in recent years, it is now feasible to revisit the problem based on the new investigational evidence. In order to discriminate between the two categories of models, we can use the following criterion temporarily: if dipping interfaces are dominant in the crust and upper mantle near the suture zone, it is most likely that the collision is

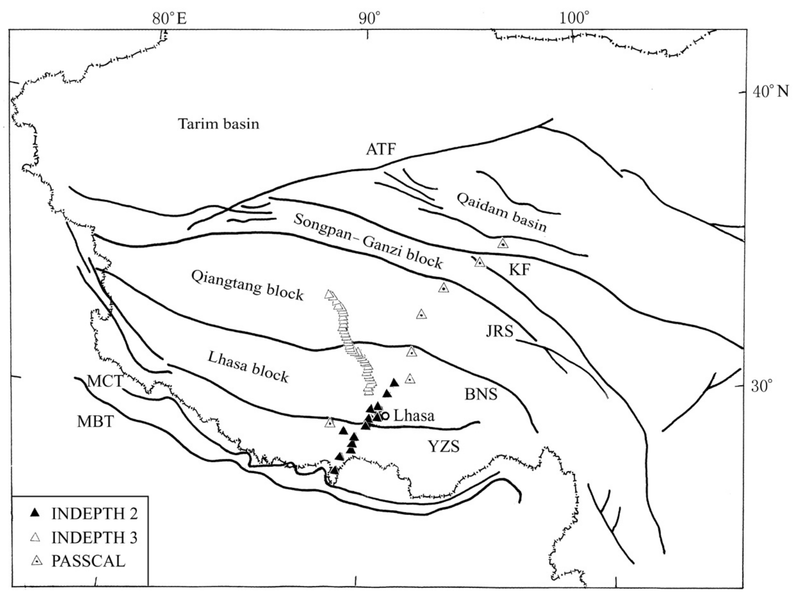


Figure 2 Tectonics of the Tibetan Plateau and locations of seismic profiles
KF: Kunlun fault; JRS: Jinsha suture; BNS: Bangong-Nujiang suture; YZS: Yarlung Zangbo suture; MCT: Main Central thrust; MBT: Main boundary thrust; ATF: Altun fault

mainly accommodated by subduction; if vertical structures are predominated near the suture zone, the collision is accommodated by horizontal compression and shortening. Such reasoning is not perfect, but it is probably the most reasonable one we can do so far.

The Tibetan Plateau experienced several continent-continent collisions in the Mesozoic (Chang and Pan, 1984; Dewey *et al*, 1988), as represented by the Kunlun, Qilian, Jinsha, and Bangong-Nujiang suture zones formed in different geological epochs. The Cenozoic India-Eurasian continent-continent collision started about 45~50 Ma ago. Based on the Sino-UK joint survey results, Chang and Pan (1984) proposed that the suture zone is along the Yarlung Zangbo river. This was supported by wide spread of ophiolites along the zone. The total length of the suture zone is over 1 000 km (Figure 2). Large structural differences exist in different segments. The collision might happen earlier in the western part, followed by collision in the east. In this paper, our investigation is mainly based on data near a profile from Lhasa to Golmud, because plenty of observations have been available along the profile.

# 1 Multiple crustal subductions

So far, the most convincing crustal structural images of the Himalaya and Tibetan Plateau came from INDEPTH seismic vertical reflection cross-sections (Figure 3) (Brown *et al*, 1996; Hauck *et al*, 1998; ZHAO *et al*, 1997). In particular, we noted the strong reflections in the lower crust beneath the Gangdise belt to the north of the Yarlung Zangbo suture. Seismic reflector just on the Yarlung Zangbo suture is uncertain due to high noise level in the seismic data. However, the southward and upward extent of the dipping reflector beneath the Gangdise belt intercepts the suture on the surface. Yin *et al* (1994), LIU (1988), and WANG (1983) reported a north-dipping fault observed near the suture zone, which was believed to be the crustal penetrating fault. Another clear reflector can be seen underneath STD (South Tibet detachment, STD for short) in Figure 3 and is named as the main Himalayan thrust (MHT) (Zhao *et al*, 1993; Owens and Zandt, 1997). It might extend southward to connect to the main central thrust (MCT) or the main boundary thrust (MBT) identified on the surface. However, its dipping angle is much less than those of MCT and MBT.

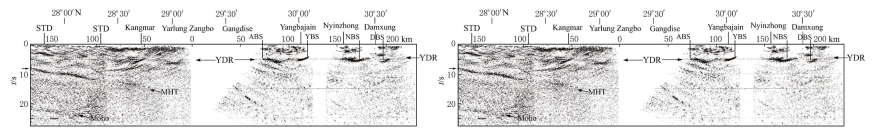


Figure 3 Vertical seismic reflection section in Himalaya and Tibet (Brown *et al*, 1996)
STD: South Tibet detachment; MHT: Main Himalayan thrust; YDR: Yadong-Gulu rift; ABS: Angang bright spot; YBS: Yangbajain bright spot; NBS: Nyinzhong bright spot; DBS: Damxung bright spot

Some researchers believe that MHT is the upper boundary of the Indian subduction plate starting at MCT or MHT. But clear MHT interface only appears under STD. It may extend to the Kangmar Dome to the north and terminate there. As mentioned above, the collision between India and Eurasia initially occurred along the Yarlung Zangbo suture. Following the consumption of oceanic lithosphere, the continental Indian lithosphere should continue to subduct beneath Eurasia there. The dipping interface beneath the Gangdise belt is most likely to be the trace of this subduction. We thus called it the Gangdise crustal thrust (GCT). Since the MCT and MBT formed after the subduction at the Yarlung Zangbo suture, they may be related to multiple crustal subductions thereafter.

The location and dipping angle of GCT agrees with the wide-angle reflection results in the Sino-French joint project (Hirn *et al*, 1984a, b; XIONG *et al*, 1985), which show several parallel interfaces, one of which coincides with the vertical reflection interface. Some wide-angle reflections under the Gangdise belt can be traced down to the uppermost mantle. So, if GCT represents traces of the Yarlung Zangbo crustal subduction, its depth may penetrate Moho to the uppermost mantle.

Another piece of evidence of the Yarlung Zangbo crustal subduction comes from the distribution of intermediate-depth earthquakes. There is a cluster of earthquakes in a depth range of 40 km to 120 km under the Himalaya and southern Tibet (ZENG and SUN, 1993; ZENG *et al*, 2000). Figure 4 shows 67 well located intermediate-depth earthquakes. 18 of them were located by using digital seismic recordings or dedicated relocations. Since the seismicity in western Tibet differs from that in eastern Tibet (ZENG and SUN, 1993), the seismic events included in Figure 4 are limited to eastern Tibet only.

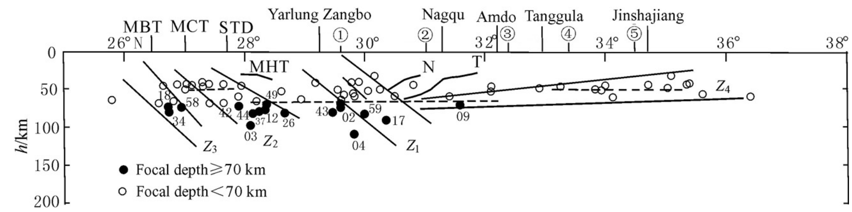


Figure 4 Location of the intermediate-depth earthquakes in the study area
① Lhasa; ② Sangxung; ③ Bangong-Nujiang; ④ Wenquan; ⑤ Erdaogou; $Z_1$, $Z_2$, $Z_3$, $Z_4$: Intermediate-depth earthquake zone; MBT: Main boundary thrust; MCT: Main central thrust; MHT: Main Himalayan thrust; STD: South Tibet detachment. N and T represent wide-angle reflective interface of middle and low crust, respectively

The most clear intermediate-depth earthquake zone is located under the Yarlung Zangbo suture. 15 earthquakes deeper than 35 km form a northward dipping zone ($Z_1$). Among them, 5 events are deeper than 70 km (No. 2, 4, 17, 43 and 59). The deepest one is event No. 4, which was investigated by Molnar and Chen (1983) and Chen *et al* (1981). Its depth is 107 km in the Chinese earthquake catalogue and 90 km by Molnar and Chen (1983). Event No. 43 is from Zhu and Helmberger (1996). Events No. 2, 4 and 43 have almost identical hypocenters. The Yarlung Zangbo intermediate-depth earthquake zone can be connected to shallow earthquakes and surficial northward dipping fault. It extends down to about 100 km depth.

Based on the existing seismic observations mentioned above, we conclude that dipping structures are predominant in the crust of the India-Eurasian collision zone, which suggests that the collision process is mainly subduction. However, it is crustal subduction in the continent-continent suture instead of whole mantle lithosphere subduction in the oceanic subduction zones. Actually, similar dipping interfaces are found in the crust of many continental collision zones (Pliffner *et al*, 1988; Choukrome and ECORS Team, 1989; Sorkhabi and Stump, 1993; Juhlin *et al*, 1996; Yang, 2000). Although fluids or shear zones are also possible explanations, crustal subduction seems the most reasonable cause for the dipping structure in the collision areas. Seismicity shows that the crustal subduction beneath Yarlung Zangbo suture is still active and it may penetrate Moho to the uppermost mantle.

Another northward dipping intermediate-depth earthquake zone, $Z_2$, appears south of the zone $Z_1$ (Figure 4). The two zones are separated by an aseismic gap between them. The zone $Z_2$ can be connected to the MCT at the surface. It consists of 15 earthquakes; seven are deeper than 70 km (No. 3, 12, 26, 37, 42, 44, and 49). Two of them (No. 42 and 44) were investigated by Zhu and Helmberger (1996). There are fewer amounts of intermediate-depth earthquakes in the zone $Z_3$. Three of them are deeper than 70 km (No. 18, 34 and 58). They helped to separate the zone $Z_3$ from the zone $Z_2$.

These intermediate-depth earthquake zones suggest multiple crustal subductions during the India-Eurasian collisions in different geological periods (ZENG *et al*, 2000). Based on seismic and geochronological results (Sorkhabi and Stump, 1993; Yin and Harrison, 2000), crustal subduction started at the Yarlung Zangbo suture at first. It was terminated after reaching the uppermost mantle owing to its light density and resistance from Eurasian mantle. As India continues to move northward, multiple crustal subductions occur along weak zones south of the suture zone later on.

No reflective interface has been detected by vertical seismic reflection north of the Gangdise belt. However, wide-angle seismic reflection results show a southward dipping interface in the lower crust south of the Bangong-Nujiang suture (Figure 4). Based on the intermediate-depth earthquake result, another earthquake zone ($Z_4$) can be identified. It dips southward slightly and may be traced as far as to Nagqu and Sangxung south of the Tanggula Mountain. Most earthquakes in the zone have depths between 40 km and 60 km except for one earthquake (No. 9) whose depth is 70 km. We suggest that there is a southward crustal subduction zone beneath the central and northern Tibetan Plateau. Its southern end is located between Sangxung and Lhasa. The northern end can be as far out as north of the Jinsha suture. More observations and data analyses are needed to confirm its existence.

## 2 Delamination of mantle lithosphere

In spite of the similarity between the India-Eurasian continent-continent collision and ocean-continent collision in which subduction is the major process, there are fundamental differences between the crustal subduction in the India-Eurasian collision and the whole lithosphere subduction in the oceanic case. The question is then where the Indian mantle lithosphere goes?

In as early as 1969, Mckenzie (1969) stated that it was questionable whether it is possible to subduct a continental lithosphere underneath another continental lithosphere owing to its lighter density and greater thickness than oceanic lithosphere. More accurate determinations of mechanic properties, especially the anelastic properties, of oceanic and continental lithospheres are needed. Since the 1980s, prevailing plastic behavior of the lower crust in continent has been recognized. The crust is likely decoupled from the underneath mantle lithosphere. This means that when crust and mantle lithosphere subduct, their speeds and directions can be different. The possibility of continental lithosphere decouple was emphasized while Willett *et al* (1993) summarized India-Eurasian collision models.

Results from global plate reconstruction and marine paleomagnetic studies indicate northward horizontal motion of the Indian lithosphere with respect to Eurasia. As mentioned above, crustal, not whole lithospheric, subductions are observed within the crust of the collision zone in Himalaya and south Tibet. Therefore, we believe that delamination of the mantle lithosphere from the crust is inevitable during the Indian subduction beneath Eurasia (ZENG *et al*, 2000). Delamination was suggested beneath the Himalaya (Bird, 1978; Bird and Baumgardner, 1981), but lacked support of geophysical observations then. ZENG *et al* (2000) proposed a new India-Eurasian collision model as shown in Figure 5a based on the above evidence of multiple crustal subduction and limited information of the upper mantle structure in the Tibetan Plateau. Chemenda *et al* (2000) suggested a different delamination model as shown in Figure 5b. The subduction directions of crust and mantle lithosphere are the same, only their subducting speed and maximum depths are different.

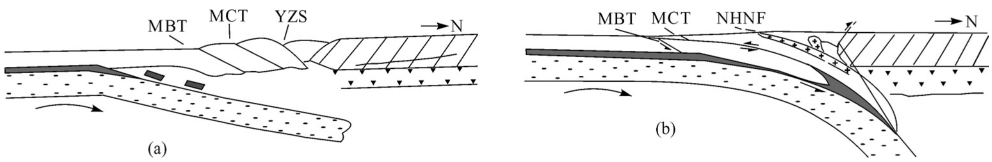


Figure 5 Two delamination models from ZENG *et al* (2000) (a) and Chemenda *et al* (2000) (b) respectively
The abbreviation NHNF represents north fault of North Himalaya and the others' meaning are same as that above-mentioned

Developing a more specific India-Eurasian collision model requires more accurate structure results of upper mantle structure of the collision zone. Active source studies can reveal Moho topography but are difficult for constraining upper mantle interfaces. There are few slab structures in the upper mantle imaged by seismic tomography in the past as they are limited by their resolution powers. Recently, several high-resolution upper mantle images have been obtained in the India-Eurasian collision zone (Kosarev *et al*, 1998; Kind *et al*, 2002) and western Pacific (Li *et al*, 2000; Li and Yuan, 2003) by stacking and migrating teleseismic receiver functions, which is quite encouraging to us.

Kosarev *et al* (1998) reported a northward dipping upper mantle interface beneath the India-Eurasian collision zone by receiver function migration and stacking of INDEPTH-2 data. They associated it with the collision process. A clearer structural image was obtained by WU *et al* (2004) using the INDEPTH-3 data (Figure 6). The northward dipping interface *AA* between the depths of 100 km and 180 km shown in Figure 6 is similar to the dipping interface by Kosarev *et al* (1998). Another dipping interface *A′A′* between latitudes 33.5°N and 35.0°N reaches to a depth of 450 km and has a similar dipping angle to *AA*. It might be the deeper extent of *AA*. One explanation for the gap between them is the possible reduction of impedance contrast of the interface as the subducting mantle lithosphere passes through the asthnosphere. Another possibility is that the two broke up during subduction. Interfaces *AA* and *A′A′* are indication of mantle lithosphere delamination and give the location of delaminated mantle lithosphere.

*BB* in Figure 6 is another band with large P-to-S conversion energy. It may be a multiple conversion in the crust or might be the bottom of the plateau's lithosphere, which is about 200 km to 250 km thick. Its discussion is outside the scope of this paper.

The 410 km discontinuity is clear in Figure 6. Its depth is 410 km between 29°N and 33°N latitudes but increases to 440 km between 33°N and 34°N latitudes. This may be caused by the *A′A′* subduction. The bottom interface of the upper mantle is clear in Figure 6 too. Its depth is about 660 km in the southern end and gradually decreases to 620 km in the northern part. Therefore, the influence of subduction may only extend to the 410 km discontinuity. The undulation of 660 km-discontinuity is controlled by other deeper processes.

There are many other intermittent horizontal conversion bands between latitudes 34°N and 35°N from Moho down to a depth of 800 km. Whether they are related to magmatic activity needs more observation data in order to be addressed.

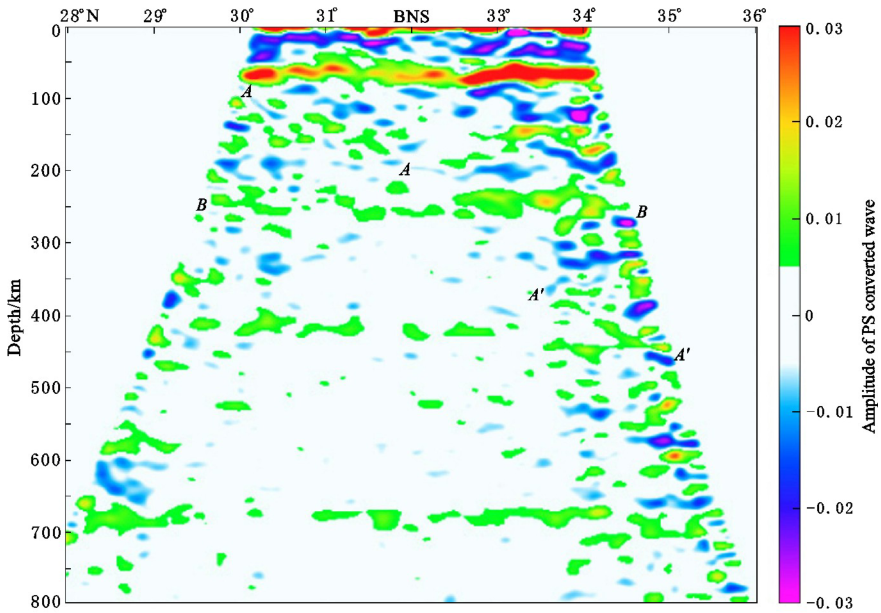


Figure 6 Upper-mantle image of the Tibetan plateau from migrating receiver functions

Kind *et al* (2002) showed a southward dipping upper mantle interface beneath northern Tibet from the INDEPTH and Sino-French data. They believed that it is resulted from Asian subduction beneath the Tibetan Plateau or obduction of the Tibetan Plateau towards Asia. But Kind *et al* (2002) did not appreciate the northward dipping interface underneath Himalaya and southern Tibet. Recently, Shi *et al* (2004) also reported this northward dipping interface, with a different interpretation. Therefore the slab structure of Figure 6 seems to be confirmed once again.

Based on the above results of crustal subduction and slab structure in the upper mantle in Figure 6 and those of Kind *et al* (2002), a schematic cross-section can be constructed to reveal major crustal and upper mantle structures related to the India-Eurasian collision process, as shown in Figure 7. Numbers 1, 2, 3 represents multiple crustal subductions beneath the Himalaya and southern Tibet. Number 4 represents possible crustal subduction of Asian block underneath the Tibetan plateau. Number 5 denotes the Indian mantle lithosphere subduction beneath Eurasia and number 6 denotes the mantle part of Asian subduction underneath Tibet or the trace of subduction of the Tibetan block towards Asia. Figure 7 shows opposing subductions of India and Eurasia in different geological time periods and delaminations of mantle lithosphere from crust during both subductions.

Teleseismic P-wave travel-time tomography by Tilmann and Ni (2003) revealed a low velocity anomaly in the depth range of 200 km to 350 km underneath the Jinsha and Kunlun sutures. Another high velocity anomaly from 100 km to 300 km beneath the Bangong suture was reported by Wittlinger *et al* (1996). They may result from the mineral differentiation due to the mantle lithosphere subductions. Similar to ocean-continental collision, mineral chemical reaction or friction heating can generate metamorphism or partial melting surrounding the subducting slab. But the location and depth of metamorphism and partial melting and the chemical and physical characteristics of metamorphic minerals are controlled by the location and depth of crustal and mantle lithosphere subductions. They are different from metamorphic belts produced by ocean-continent collision.

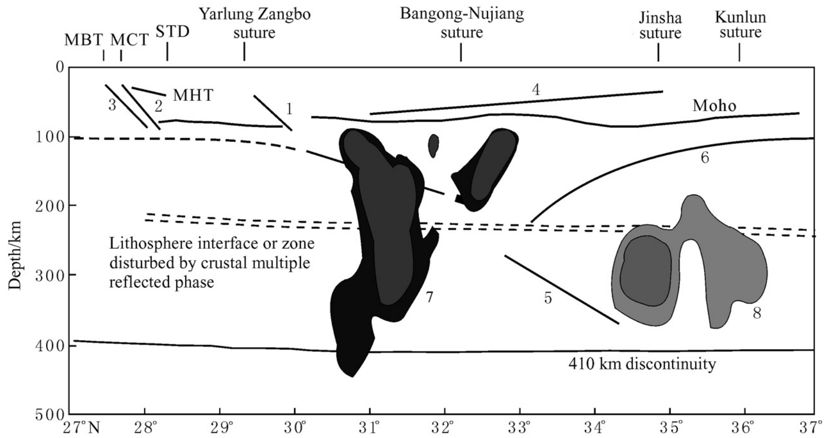


Figure 7 Crustal and upper-mantle structure and the India-Eurasian collision process
1-4 are crustal subductions; 5 and 6 are mantle lithosphere subductions; MHT is the crustal reflector under the Himalaya; 7 is a high seismic velocity anomaly; 8 is a low seismic velocity anomaly

# 3 Conclusions

We conclude that:

1) Existence of dipping slabs in the crust and upper mantle beneath the Yarlung Zangbo suture suggests the India-Eurasian collision is mainly accommodated by subduction;

2) In contrary to ocean-continental collisions, crustal subduction, rather than lithosphere subduction, is detected beneath the suture zone;

3) We also detected a northward dipping slab in the upper mantle north of the Yarlung Zangbo suture, which extends to 400 km deep and is believed to be the trace of the Indian subducting plate;

4) Different from ocean-continent collisions, mantle lithosphere inevitably delaminates from crust during the India-Eurasian collision;

5) There are opposing subductions of Indian and Eurasian Plates beneath the Tibetan Plateau in different geological time periods;

6) Crustal and mantle lithosphere subductions in the India-Eurasian collision cause physical and chemical changes of minerals in the surrounding media of subducting slab that produce seismic velocity anomalies.

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## References


Barazangi M and Ni J. 1982. Propagation characteristics of Pn beneath the Himalayan and Tibetan Plateau: Possible evidence for underthrusting of Indian continental lithosphere beneath Tibet [J]. *Geology*, **10**: 179-185.

Barazangi M and Ni J. 1984. Seismotectonics of the Himalayan collision zone: Geometry of the underthrusting Indian Plate beneath the Himalaya [J]. *J Geophys Res*, **89**: 1 147-1 163.

Beghoul N, Barazangi M, Lsacks B L. 1993. Lithosphere structure of Tibet and western North America: Mechanics of uplift and a comparative study [J]. *J Geophys Res*, **98**: 1 997-2 016.

Bird P. 1978. Initiation of intracontinental subduction in the Himalaya [J]. *J Geophys Res*, **83**: 4 975-4 987.

Bird P and Baumgardner J. 1981. Steady propagation of delamination events [J]. *J Geophys Res*, **86**: 4 891-4 903.

Brown L D, Zhao W, Nelson K D, *et al*. 1996. Bright spots, structure and magmatism in southern Tibet from INDEPTH seismic reflection profiling [J]. *Science*, **274**: 1 688-1 690.

Chang C and Pan Y. 1984. The structure and evolution of the Qinghai-Xizang (Tibet) Plateau [C]//Academia Sinica. *Developments in Geoseience Contribution to* 27*th International Geological Congress*, *Moscow*. Beijing: Science Press.

Chemenda A I, Burg J P, Mattauer M. 2000. Evolutionary model of the Himalaya-Tibet system: Geopoem based on new modeling, geological and geophysical data [J]. *Earth Planet Sci Lett*, **174**: 397-409.

Chen W P, Nabelek J L, Fitch T J, *et al*. 1981. An intermediate depth earthquake beneath Tibet: Source characteristics of the event of September 14, 1976 [J]. *J Geophys Res*, **86**(B4): 2 863-2 876.

Choukrome P and ECORS Team. 1989. The ECORS Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt [J]. *Tectonics*, **8**: 23-29.

Dewey J F, Shackelton R, Chang C, *et al*. 1988. The tectonic evolution of the Tibetan Plateau [J]. *Phil Trans Roy Soc Lond*, **A327**: 379-413.

England P C and Houseman G A. 1986. Finite strain calculations of continental deformation, 2: Comparison with the India-Asia collision [J]. *J Geophys Res*, **91**: 3 664-3 676.

Hauck M L, Nelson K D, Brown L D, *et al*. 1998. Crustal structure of the Himalayan orogen at ~90° east longitude from Project INDEPTH deep reflection profiles [J]. *Tectonics*, **17**(4): 481-500.

Hirn A, Lepine J C, Jobert G, *et al*. 1984a. A crustal structure and variability of Himalaya border of Tibet [J]. *Nature*, **307**: 23-25.

Hirn A, Nercessian A, Sapin M, *et al*. 1984b. Lhasa block and bordering sutures: A continuation of a 500 km Moho traverse through Tibet [J]. *Nature*, **307**: 25-27.

Houseman G A and England P C. 1996. A crustal-thickening model for the Indo-Asian collision [M]//Yin A and Harrison T M. *The Tectonic Evolution of Asia*. New York: Cambridge University Press: 1-17.

Juhlin C, Knapp J H, Kashubin S, *et al*. 1996. Crustal evolution of the Middle Urals based on seismic reflection and refraction data [J]. *Tectonophysics*, **264**: 21-23.

Kind R, Yuan X, Saul J, *et al*. 2002. Seismic images of crust and upper mantle beneath Tibet: Evidence for Eurasian Plate subduction [J]. *Science*, **298**: 1 219-1 221.

Kosarev G, Kind R, Sobolev S V, *et al*. 1998. Seismic evidence for a detached Indian lithospheric mantle beneath Tibet [J]. *Science*, **283**: 1 306-1 309.

Li X and Yuan X. 2003. Receiver functions in northeast China: Implications for slab penetration into the lower mantle in northeast Pacific subduction zone [J]. *Earth Planet Sci Let*, **216**: 679-691.

Li X, Sobolev S V, Kind R, *et al*. 2000. A detailed receiver function image of the upper mantle discontinuities in the Japan subduclion zone [J]. *Earth Planet Sci Let*, **183**: 527-541.

LIU Zeng-qian. 1988. *Geological Map of Qinghai-Xizang Plateau and Its Neighboring Regions*, *Scale* 1:500 000 [M]. Beijing: Geological Publishing House (in Chinese)

Lsacks B L, Oliver J, Sykes L R. 1968. Seismology and the new global tectonics [J]. *J Geophys Res*, **73**: 58 85-59 00.

Mattauer M. 1986. Intracontinertal subduction, crust mantle decollement and crustal stacking wedge [G]//Coward M P and Ries A. *Collision Tectonics*. London: Geol Soc Spec Publ: 35-60.

Matte Ph, Mattauer M, Oliver J M, *et al*. 1997. Continental subductions beneath Tibet and the Himalayan orogeny: A review [J]. *Terra Nova*, **9**: 264-270.

Mckenzie D P. 1969. Speculations on the consequences and causes of plate motions [J]. *Geophys J Roy astr Soc*, **18**: 1-32.

Molnar P and Chen W P. 1983. Focal depths and fault plane solutions of earthquakes under the Tibetan Plateau [J]. *J Geophys Res*, **88**(B2): 1 180-1 196.

Owens T J and Zandt G. 1997. Implications of crustal property variations for model of Tibetan Plateau evolution [J]. *Nature*, **387**: 37-43.

Pliffner O A, Frei W, Finckh P, *et al*. 1988. Deep seismic reflection profiling in the Swiss Alps: Explosion seismology results for line NFP 20-East [J]. *Geology*, **16**: 987-990.

Seeber L, Ambruster J G, Quittmeyer R C. 1981. Seismicity and continental subduction in Himalayan arc [G]//Guppta H K, Delany F M. *Zagros*, *Hindu Kush*, *Himalaya*, *Geodynamic Evolution*. Washington: AGU: 215-242.

Shi Da-nian, Zhao Wen-jin, Brocon L, *et al*. 2004. Detection of southward intracontinental subductions of Tibetan lithorphere along the Bangong-Nujiang suture by P-to-S the converted waves [J]. *Geology*, **32**(3): 209-212.

Sorkhabi R B and Stump E. 1993. Rise of the Himalaya: A geochronologic approach [J]. *GSA Today*, **3**(4): 87-92.

Tapponnier P and Molnar P. 1997. Active faulting and tectonics in China [J]. *J Geophys Res*, **82**: 2 905-2 930.

Tapponnier P, Xu Z, Roger F, *et al*. 2001. Oblique stepwise rise and growth of the Tibet Plateau [J]. *Science*, **294**: 161-167.

Tilmann F and Ni J. 2003. INDEPTH III seismic imaging of the downwelling Indian lithosphere beneath central Tibet [J]. *Science*, **300**: 1 424-1 427.

Van der Hilst R D, Widiyantoro S, Engdahl E R. 1997. Evidence for deep mantle circulation from global tomography [J]. *Nature*, **386**: 578-584.

WANG Xi-bin. 1983. *Geologic Map of the Xigatze-Zedong Region*, *Scale* 1:100 000, *Xizang* (*Tibet*) *With Report* [M]. Lhasa: Xizang Bureau of Geology (in Chinese).

Willett S, Beaumont C, Fullsack P. 1993. Mechanical model for the tectonics of doubly vergent compression orogens [J]. *Geology*, **21**: 371-374.

Wittlinger G, Masson F, Poupinet G, *et al*. 1996. Seismic tomography of northern Tibet and Kunlun: Evidence for crustal blocks and mantle velocity contrasts [J]. *Earth Planet Sci Let*, **139**: 263-276.

WU Qing-ju, ZENG Rong-sheng, ZHAO Wen-jin. 2005. The upper mantle structure of the Tibetan Plateau and its implication for the continent-continent collision [J]. *Science in China*, **48**(8): 1 158-1 164.

XIONG Shao-bai, TENG Ji-wen, YIN Zhou-xun. 1985. The thickness of the crust and undulation of discontinuity in Xizang (Tibet) Plateau [J]. *Chinese J Geophys*, **28**(Suppl.): 16-27 (in Chinese).

YANG Wen-cai. 2000. Analysis of deep intracontinental subduction [J]. *Episodes*, **23**(1): 20-24.

Yin A and Harrison T M. 2000. Geological evolution of the Himalaya-Tibetan orogeny [J]. *Annu Rev Earth Planet Sci*, **28**: 211-280.

Yin A, Harrison T M, Ryerson F J, *et al*. 1994. Tertiary structural evolution of the Gangdese thrust system, southern Tibet [J]. *J Geophys Res*, **99**(B9): 18 175-18 201.

ZENG Rong-sheng and SUN Wei-guo. 1993. Seimicity and focal mechamism in Tibetan Plateau and its implications to lithospheric flow [J]. *Acta Seismologica Sinica*, **6**(2): 261-287.

ZENG Rong-sheng, DING Zhi-feng, WU Qing-ju, *et al*. 2000. Seismological evidence for multiple incomplete crustal subduction beneath the Himalayas and southern Tibet [J]. *Chinese J Geophys*, **43**(6): 780-797 (in Chinese).

Zhao W, Nelson K D, INDEPTH Project Team. 1993. Deep seismic reflection evidence for continental underthrusting beneath southern Tibet [J]. *Nature*, **366**: 557-559.

ZHAO Wen-jin, Nelson K D, XU Zhong-xin, *et al*. 1997. Double intracontinental underthrusting structure of the Yarlung Zangbo suture and different molten layers: A comprehensive study of INDEPTH's results [J]. *Chinese J Geophys*, **40**(3): 325-336 (in Chinese).

Zhu L and Helmberger D V. 1996. Intermediate depth earthquakes beneath the India-Tibet collision zone [J]. *Geophys Res Lett*, **135**: 435-438.