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Tomographic evidence for wholesale underthrusting of India beneath the entire Tibetan plateau

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Abstract

We analyzed a global tomographic model for the Tibet-Himalayan collision zone, which indicates that the Indian lithospheric slab has been subducted subhorizontally beneath nearly the entire Tibetan plateau to depths of 165-260 km. Tibetan velocity structure is low in its crust and high in its lithospheric mantle at depths between 75-120 km. We interpret an asthenospheric layer positioned above the subducted Indian slab at depths between 120-165 km beneath the Tibetan plateau. Beneath the central portion of the plateau a low-velocity anomaly exists from the crust down to 310 km depth, indicating mantle upwelling through a weakened part of the subducted slab. We present a model, which explains that, the uplift history and low relief of the Tibetan plateau is a result of subhorizontal subduction and heating of Indian lithosphere that is separated from Tibetan lithosphere by a thin channel of asthenosphere. Two predictions made by our model are: 1) the amount of shortening in the Himalayas is equivalent to the amount of underthrusted Indian mantle lithosphere and; 2) a young mantle geochemical signature should be present along the entire southern portion of the Tibetan plateau.

Keywords: Seismic tomography; Tibetan plateau; subduction; underthrusting; India; Himalaya
1. Introduction

Continent-continent collision leading to orogenesis, which may ultimately result in the development of supercontinents, is a fundamental tectonic process that has significantly affected the character of Earth’s surface for at least the past one billion years. In order to characterize the dynamics of continent-continent collisions, it is essential to define its present geometry and physical state. This is especially true for the largest active continent-continent collision zone on Earth, the Himalayan-Tibetan orogen. The northward convergence of India into Asia over the past 50 Ma (Patriat and Achache, 1984; Dewey et al., 1988) is intimately linked to the creation of the Tibetan plateau and has impacted the tectonic framework throughout Asia since Cenozoic time (Molnar and Tapponnier, 1975; Yin and Harrison, 2000). The challenge of unraveling the evolution of the Tibet-Himalayan orogen, and specifically the uplift history of the Tibetan plateau, has been significantly bolstered by the collection of a wide-variety of geologic and geophysical information. Nevertheless, unresolved issues remain regarding the mechanisms by which the convergence between India and Asia was accommodated and the Tibetan plateau was uplifted.

Models that explain the Cenozoic uplift of the Tibetan plateau can be differentiated from one another by the predictions they make regarding the lithospheric structure beneath the Tibetan plateau: a) Complete underthrusting of the Indian plate (Argand, 1924; Powell and Conaghan, 1973; Powell, 1986) or portions of it beneath Tibet (DeCelles, et al., 2003); b) Lithospheric thickening by distributed thrust faulting (Dewey and Burke, 1973; Chang, C., et al., 1986; England and Houseman, 1989) and attendant convective removal of overthickened mantle lithosphere (England and Houseman, 1989;
Houseman and Molnar, 2001); and d) Intracontinental subduction along reactivated sutures (Meyer, B., et al., 1998). A necessary first step towards assessing the merits of these models is a thorough description of the geometry and physical state of the lithospheric structure in this region.

This paper provides new insight into the lithospheric structure beneath the Tibetan plateau based on analyzing a high-resolution global tomographic model (Zhou, 1996). Two surprising results are the presence of a slab-shaped high seismic velocity anomaly beneath nearly the entire Tibetan plateau that we interpret to be subducted Indian lithospheric mantle, and an overlying wedge-shaped, slow seismic velocity anomaly interpreted as an asthenospheric layer (Fig. 1). Not only does this seismic structure set boundary conditions for geodynamic modeling of the Tibet-Himalayan collision zone, it also supports an inference for the cause of the destructive earthquake that occurred in western India on 26/01/01.

2. Observations from a global tomography

Seismic tomography provides a snapshot of the deep Earth structure as expressed by its seismic properties, based on traveltimes of seismic waves propagating from earthquake or man-made sources to seismological stations. In deriving tomographic models at regional scales, data from sources or receivers outside the model area are usually used to enhance the data coverage. Since there are few seismological stations in Tibet, for example, it is necessary to use outside sources and stations that have rays traversing beneath Tibet. A dilemma in using raypaths partially outside of the model area is that the gain in data quantity is at the expense of bringing potential contaminations
from outside. However, this dilemma can be overcome by using a global model that leaves no outside areas, if the model has high enough resolution (Zhou, 1996; Bijwaard, et al., 1998). In this study, we analyze a high-resolution global tomographic model called $P1200$ that describes the $P$-wave velocity variations from the surface down to 1200 km depth (Zhou, 1996), using cell size of 1° laterally and 35-50 km vertically. Although lateral heterogeneities below 1200 km depth could have small effects on steep-dipping features at shallow depths, most velocity anomalies interpreted in this paper are of subhorizontal geometry and therefore not affected much by deep mantle anomalies through deep-diving rays.

Fig. 2 shows nine depth slices of the $P1200$ model from the surface down to 410 km depth across the Himalayan-Tibetan collision zone. The abundance of earthquakes in the region and its surrounding areas helps to constrain the velocity anomalies. The images on the depth slices are dominated by coherent velocity anomalies greater than $10^\circ \times 10^\circ$ in lateral dimensions, although there are also smaller anomalies. The resolution of the data has been tested using checkerboard impulse resolution tests (Zhou, 1988; Zhou and Clayton, 1990). As shown in Fig. 3, except some corner areas at shallow depth ranges, excellent results are achieved throughout the region at a resolution of 3° laterally and about 150 km vertically.

The good resolution result as shown in Fig. 3 is largely due to the use of global data set that contains many rays with neither sources nor stations inside Tibet, such as earthquakes in central Asia that were recorded by Chinese stations. The resolution tests suggest that the velocity anomalies interpreted in this paper would be reliable if the signal to noise ratio of the data is also sufficient. One concern is from mantle anomalies below
1200 km depth. For the subhorizontal, high-amplitude, and shallow structures interpreted in this paper, however, the contamination from mantle anomalies below 1200 km depth is relatively small. The processing of the ISC traveltime data for the tomographic inversion included corrections for station statics, hypocentral re-determination, and use of summary ray culling (Zhou, 1996). The model was constrained by the multi-scale inversion that improve the handling of uneven ray coverage. Nevertheless, to reduce the bias of our interpretation, the full array of depth slices and cross sections are presented here.

As shown in Fig. 1 and 2, low velocities characterize the thick crust of Tibet from the surface down to 75 km depth. In the 0-35 km depth slice two low-velocity zones extend from the Tien Shan through western Tarim to western Tibet, and from the eastern edge of Tibet southwards to the Gulf of Thailand. These anomalies persist in the second depth slice, which reveal two additional low velocity patches; one in central Tibet between 82ºE and 93ºE, and the other beneath western Mongolia and the Qilian Shan. The slow anomaly in the central Tibet continues in deeper slices to at least 310 km depth, and is narrowing with depth to be within 84ºE and 91ºE around 300 km depth. In the 165-260 km depth range, the region is actually faster than the layers’ average values, but slower than the rest of the high-velocity slab.

We interpret the extremely coherent, slab-shaped high-velocity anomaly in the four depth slices from 75 to 260 km in Fig. 2 as Indian mantle lithosphere. On the 75-120 km depth slice, for example, the appropriate shape of a combined India and Tibet is discernable as the largest high-velocity anomaly. In contrast, on the 120-165 km depth slice, there is a northwest-trending low-velocity anomaly from Tarim to central Tibet. This slow anomaly appears to be connected with the low-velocity anomaly in the Bay of
Bengal. At the same depth range to the southwest, a northwest-trending high-velocity feature stretches from the Aral Sea to central India, and another high-velocity anomaly exists from eastern Tibet to the Burma arc. On the 165-210 km and 210-265 km depth slices, the Indian lithospheric mantle is the most coherent high-velocity anomaly that extends northwards beneath nearly the entire Tibetan plateau. Results from these two depth slices have been stacked vertically to produce the depth slice of the subducting Indian slab shown in Fig. 1. In the deepest three depth slices of Fig. 2 the coherent high-velocity anomaly in India and Tibet disappears, and the largest high-velocity anomaly on these slices is north of 40°N.

A comparison between the depth slices in Fig. 2 reveals that the high-velocity Indian lithospheric mantle anomaly is shifted north-northeasterly as it plunges deeper, manifesting a subduction pattern. As seen in cross sections A-A1, B-B1, and D-D1 in Fig. 4, the high-velocity Indian slab starts to dip towards the Tibetan plateau hundreds of kilometers south of the Himalayas. Beneath the Tibetan plateau a low-velocity layer, which we interpret as a thin asthenospheric layer, exists between the high-velocity Tibetan lithospheric mantle and the subducted high-velocity Indian slab. Cross section C-C1 traverses through the anomalous low-velocity area in central Tibet and will be compared later with another study. At lower-mantle depths beneath India (cross sections A-A1, B-B1, and D-D1) there is a large, high-velocity anomaly that has been interpreted as the subducted Tethyan oceanic slab (Van der Voo, et al., 1999). A complete set of cross sections is shown in Fig. 5, with eleven dip sections (E-E1 to O-O1) and three strike sections (P-P1 to R-R1) with respect to the orogenic front in the central Himalaya.
A general interpretation can be drawn from the depth slices and cross sections. The Indian lithospheric slab is clearly subducted horizontally beneath the Tibetan plateau. Above the subducted Indian slab, the Tibetan lithosphere has an abnormally low-velocity crust and a high-velocity lithospheric mantle above 120 km depth. In the depth range of 120-165 km a low-velocity layer exists which we interpret as an asthenospheric layer between the Tibetan lithosphere and the subducted Indian slab. The subducted Indian slab is very strong west of 85ºE and east of 93ºE (Fig. 1). In central Tibet, between 85ºE and 93ºE and north of the Indus-Yalu suture zone, there is a low-velocity area within the subducted slab. This area is part of a low velocity anomaly that extends vertically from 35 km down to at least 310 km in depth. Interestingly, many previous studies in Tibet were conducted in the area over this anomaly, and have found features such as low seismic velocities and indications of partial melting and a mantle-originated geochemical anomaly (McNamara, et al., 1994; Nelson, et al., 1996; Kind, et al., 1996; Turner, et al., 1996; Owens and Zandt, 1997; Yuan, et al., 1997; Makovsky and Klemperer, 1999; Kosarev, et al., 1999; Hoke, et al., 2000).

3. Comparison with previous studies

The unique nature of Tibetan plateau has attracted a large number of previous seismologic studies. During the 1990’s, for instance, there were findings of high S-wave velocities under westernmost Tibet and the Karakorum, and low velocities under central Tibet (Molnar, 1990; Woodward and Molnar, 1995), low Pn velocity region in north central (Zhao and Xie, 1993; McNamara, et al., 1997), and high P-wave velocities beneath southern Tibet (Pandey, et al., 1991). The deep seismic velocity structure
analyzed in this paper is consistent with many of the previous studies. For instance, the lower mantle high-velocity anomaly beneath northern India as shown in Fig. 4 is similar to the shallow portion of a large high-velocity belt mapped by Van der Voo et al. (1999). These investigators interpreted it as a subducted Tethyan oceanic slab that extends laterally from the Mediterranean Sea to the Andaman Sea and deepens to at least 2000 km in depth. The low-velocity anomaly mapped and interpreted as the signature of the Deccan plume by Kennett and Widiyantoro (1999) can also be seen in the 35-75 km depth slice in Fig. 2, though the anomaly occurs slightly to the south in the P1200 model. From the two depth slices by these authors at 100 km and 250 km depths, one can infer similar patterns of the Indian slab as shown in the corresponding depth slices in Fig. 2. In fact, the high-velocity Indian slab in Fig. 1 matches well with the configuration of the high-velocity anomaly in the 200 km panel of Plate 1 by Bijwaard et al. (1998). The S-wave velocity map at 100 km depth by Villaseñor et al. (2001) also show that the high-velocity Indian slab anomaly extends into the western part of Tibet and that the central part of Tibet has a large low-velocity region as seen in Fig. 1 in this paper.

Zhou et al. (1996) conducted a careful modeling study of differential residual sphere data for four Tibetan earthquakes. Their best fitting model consists of a narrow, nearly vertical, high velocity slab extending to at least 400 km beneath the southern Tibetan plateau. As shown in Fig. 2 and 5, the P1200 model also contains a high velocity slab at similar location, though the slab in the P1200 model stays above 300 km and extends northward subhorizontally. Fig. 6 shows the predicted differential residual spheres from the P1200 model for the same four events (Zhou et al., 1996). The level of fitness with the differential residual sphere data is compatible between predictions by the
P1200 model in Fig. 6 and that by the model of Zhou et al. (1996). Hence a subhorizontal Indian slab offers a compatible possibility for the differential residual sphere data.

Before the 1990’s most seismologic studies of the Tibetan deep structure were aimed at constraining large-scale features using stations mostly outside the plateau (Roecker, 1982; Ni and Barazangi, 1983; Jobert, et al., 1985; Molnar, 1988). In the last decade, there have been several deployments of seismologic arrays, such as the PASSCAL experiment (McNamara, et al., 1994; Owens and Zandt, 1997) and the INDEPTH II/GEODEPTH experiment (Nelson, et al., 1996; Kind, et al., 1996; Yuan, et al., 1997; Nelson, et al., 1996; Kind, et al., 1996; Yuan, et al., 1997; Makovsky and Klemperer, 1999) across the central and southern Tibet. Interestingly, these studies were conducted within the area over the low-velocity anomaly shown in Fig. 1 and 2. Our study demonstrates that this low-velocity feature extends down to at least 310 km depth. This feature is consistent with the presence of volcanic activity (Turner, et al., 1996) and indications of partial melting in the lower crust (Owens and Zandt, 1997; Nelson, et al., 1996; Kind, et al., 1996).

Although the P1200 model is of lower resolution compared to that of regional array studies, the former has a much broader spatial coverage. Therefore, a comparison between the two may assist in extrapolating the array data laterally. Cross section C-C1 in Fig. 4 features a comparison with the receiver function image of the eastern Tibetan plateau by Kosarev et al. (Kosarev, et al., 1999), who found that on this traverse the Moho depth reaches to its maximum depth of 80 km near 30ºN latitude, and becomes shallower toward the north. Cross section C-C1 shows a low-velocity anomaly in the top
100 km depth range beneath most of the Tibetan plateau. The lower boundary of this slow anomaly follows closely to the interpreted Moho profile from the receiver function study. The lower boundary also reaches its deepest point near 30°N and becomes shallower toward the north.

An alternative explanation for the first-order seismic structure beneath Tibet (high-velocity zones in the east, west, and south and a slow-velocity zone underneath north-central Tibet) is that it reflects temperature variations in the Tibetan upper mantle associated with small-scale mantle convection (Molnar, P., 1990; Woodward and Molnar, 1995; McNamara, et al., 1997; Pandey, et al., 1991). As expressed in Molnar (Molnar, 1988) north-central Tibet may reflect a region where previously thickened mantle lithosphere is being convectively thinned and is flanked on the east and west by downwelling mantle lithosphere. Since subduction of the Indian plate is occurring, mantle convection beneath parts of Tibet must certainly be occurring also. Nevertheless, the geometry and position of the Indian slab places limits on where convection may be occurring. More conservative interpretations than ours indicate that the Indian slab shallowly-dips beneath Tibet ~350 km north of the Indus-Yalu suture zone (Owens and Zandt, 1997; Kosarev, et al., 1999). Although, as mentioned earlier, these studies were conducted in the central portions of the Tibetan plateau, extrapolating this position to the west, places the Indian slab in a region where downwelling of Tibetan mantle lithosphere is inferred (Zhou, et al., 1996). Another short-coming of the mantle lithosphere convection model is that it does not provide an explanation for a young mantle geochemical signature observed in geothermal spring samples (Hoke, et al., 2000) nor early Miocene high-K volcanic rocks in southwest Tibet (Miller, et al., 1999).
4. Implications

Much of the Tibetan plateau is flat with an average elevation of 5 km (Fielding, et al., 1994), and its crust is about twice as thick as the crust elsewhere (Jobert, et al., 1985; Molnar, 1988). The seismic images analyzed in this study require that any theory seeking to explain the uplift history of the Tibetan plateau include the existence of Indian lithospheric slab beneath the western and eastern portions of the Tibetan lithosphere. Less clear in the seismic images is the presence of low-velocity channel, interpreted as asthenosphere, sandwiched between the Indian and Tibetan lithosphere.

Our proposed interpretation of the lithospheric structure is similar in various aspects to other previously published models involving underthrusting of Indian lithosphere beneath Tibet (Argand, 1924; Powell and Conaghan, 1973; DeCelles, et al., 2003; Chemenda, et al., 2000). We discuss below testable predictions made by our model concerning the geologic evolution of the Himalaya and Tibetan plateau.

4.1 Comparison with crustal shortening estimates

Assuming that a lithospheric-scale detachment separating Tibetan lithosphere from Indian lithosphere exists along strike of the orogen (Zhao, W., et al., 1993), our interpretation that Indian mantle lithosphere has been underthrust northward beneath Tibet to the Jinsha suture (Fig. 7) predicts the magnitude of crustal shortening of rocks within the Himalaya. On the 165-210 km and 210-265 km depth slices (Fig. 2), the Indian lithospheric mantle is the most coherent high-velocity anomaly that extends northwards beneath nearly the entire Tibetan plateau to approximately 36°N in latitude. This latitude is, for the western Tibet, around its boundary with the Tarim Basin and, for
the eastern Tibet, around its boundary with the Qaidam basin. Zhu and Helmberger (1998) found a 15-20 km step change in Moho depth between the thick Tibetan crust and relative thinner Qaidam basin crust.

The above model places the Indian lithospheric slab 570 km north of the Indus-Yalu suture zone in southwest Tibet (Fig. 7). DeCelles et al. (1998) calculated ~228 km of horizontal shortening of the Subhimalaya and Lesser Himalaya, and later refined this estimate with detailed mapping along the Seti River corridor to 460 km (DeCelles, et al., 2001). A minimum-shortening estimate for the Dadeldhura thrust and Main Central Thrust is 117 km (DeCelles, et al., 2001). Along the Seti and Karnali river corridors considerably more shortening is required if both thrusts reached as far south as the Dadeldhura synform (DeCelles, et al., 2001; Upreti and Le Fort, 1999). Srivastava and Mitra (1994) estimated between ~193 and 260 km on the Main Central Thrust and Almora thrust (equivalent to the Dadeldhura thrust) in northern India. Combining the shortening estimates for the Subhimalaya and Lesser Himalaya along the Dadeldhura-Baitadadi road transect (DeCelles et al., 1998) (Fig. 7b), the Main Central Thrust and Almora thrust (Srivastava and Mitra, 1994), and the Tethyan fold-thrust belt and Indus-Yalu suture zone (Murphy and Yin, 2003), yields a total horizontal shortening estimate across the central Himalaya in western Nepal and southwest Tibet of 597-664 km.

Alternatively, combining the shortening estimates along the Seti River corridor (DeCelles, et al., 2001) with those in the Tethyan fold-thrust belt and Indus-Yalu suture zone yields a total shortening estimate of 763 km, which is clearly a minimum estimate since internal deformation of the metamorphic rocks in the High Himalaya is not accounted for. This amount of crustal shortening is sufficient to explain Indian mantle
lithosphere to latitude of the Jinsha suture separating the Qiangtang terrane from the Songpan Ganzi-Hoh Xil terrane (Yin and Harrison, 2000) (Fig. 7). A similar conclusion was reached by Decelles et al. (2003) who used shortening estimates from several parts of the Himalaya to suggest that portions of Indian lithosphere have been underthrust beneath Tibet to 36°N latitude. What is different about the two models is in the interpretation of the lithospheric structure beneath north-central Tibet. In the model by Decelles et al. (2003) the Indian mantle lithosphere has been delaminated leaving behind lower crust that was previously beneath the Greater Himalaya crystalline sequence. In our model, the Indian mantle lithosphere has subducted at steeper angle in north-central Tibet, and is separated from the shallowly subducted slab to the west and east by lithospheric tears.

4.2 Late Cenozoic mantle-derived magmatism in southern Tibet

The presence of a thin channel of asthenosphere between underthrusted Indian mantle lithosphere and Tibetan lithosphere provides a mechanism to generate mantle-derived melts beneath the Tibetan plateau. Our interpreted seismic structure predicts that a young mantle geochemical signature exists in along the entire southern portion of the Tibetan plateau, which differs from other models that restrict this signature to northcentral Tibet (Molnar, et al., 1993). Two studies have essentially tested this prediction. Miller et al. (Miller, et al., 1999) conducted a major and trace element study of volcanic rocks in southwest Tibet. Their results indicate that mantle-derived high-K, calc-alkaline magmatism did not end until 17 Ma. A recent ³He study (Hoke, et al., 2000) of geothermal spring samples from the Tibetan plateau, which included samples from southwest Tibet, argues for degassing of volatiles from young mantle-derived melts
intruded into the crust. Their results indicate the presence of mantle-derived helium exists along the entire southern margin of the Tibetan plateau adjacent to the Indus-Yalu suture zone. Combining the results from both these studies indicate that conditions appropriate for melting of mantle lithosphere persisted in southern Tibet since the Miocene.

4.3 Thermal effect on buoyancy of Indian lithosphere

The coherent high-velocity Indian slab anomaly exists beneath most of the Indian subcontinent and nearly the entire Tibetan plateau. This indicates that the Indian lithosphere is strong due to its great thickness, which is more than 200 km at its core beneath northern India. In contrast, the Tibetan lithosphere has a very thick and low velocity crust and a thin lithospheric mantle. Although the thickness and velocity of the Tibetan crust may have been altered during the post-collision period, the Tibetan slab was most likely warmer than the Indian slab prior to their collision given that it has been a locus of deformation since the Mesozoic (Yin and Harrison, 2000). The Indian lithospheric slab is twice as thick as that of an oceanic slab, but not as cold as the latter. The seismic velocity of oceanic slabs is 3-5% higher than the ambient region at shallow depths (Zhou and Clayton, 1990; van der Hilst, et al., 1991), while the Indian slab is only 2-3% higher near surface. In fact, as shown in cross sections B-B1 and D-D1 in Fig. 4, the slab appears losing its amplitude of high-velocity as it subducts to the north, suggesting the slab may be heating up. This implies that, though the cold continental Indian slab could subduct, its negative buoyancy is far less than that of oceanic slabs. The Indian slab possibly reached zero buoyancy at a depth around 210 km, as indicated by the subhorizontal geometry of the subduction trajectory (Fig. 4 and 5). Further
convergence of the two plates is interpreted to have resulted in underthrusting-type horizontal subduction. As the subducted or under-thrusted slab is heated up, it is predicted to change to positive buoyancy that will effectively lift the overlying Tibetan lithosphere and asthenosphere. Heating of the Indian slab is certainly enhanced by the slow convergence rate of ~ 20mm/yr between the two plates (Bilham, et al., 1997).

Hence, we hypothesize that the support to the Tibetan plateau to maintain its high elevation is most likely driven, at least partially, by the buoyancy of the heated subducted Indian slab. The much more yielding asthenospheric layer at 120-165 km depth may provide a cushion to help maintain the flatness of the plateau, similar to the mechanism suggested by models involving hydraulic uplift by injection of Indian continental crust into a fluid-like Tibetan lower crust (Zhao and Morgan, 1987) or crustal thickening by lower crustal flow (Royden, et al., 1997).

We explore this hypothesis using a simple thermal model by placing a slab of constant initial temperature into a mantle of constant temperature. With time the temperature of the slab will approach to that of the mantle. Fig. 8 shows, for different slab thickness, the time required for the slab to lose one half of its initial temperature difference from the mantle. Since the Indian slab is a continental plate, its buoyancy with respect to the mantle should turn from negative to positive after losing a portion of its temperature difference with respect to the mantle. Although we do not know how much the portion is for the Indian slab, Fig. 8 predicts the trend. For instance, we estimate it took 36 Ma for a 140-km-thick slab to lose half of its initial temperature difference. This estimated time for the slab to switch from negative to positive buoyancy, and therefore
assist in supporting the Tibetan lithosphere, is reasonable with previous estimates on the timing of plateau uplift (Harrison, *et al.*, 1995; Garzione, *et al.*, 2000).

4.4 The low-velocity anomaly beneath central Tibet

An intriguing feature in the tomographic model is a large low-velocity anomaly north of the Indus-Yalu suture zone and between 85°E and 93°E beneath the Tibetan plateau. This anomaly can be traced from the crust down to at least 310 km depth, though at depths of 75-120 km and 165-260 km (Fig. 2) it is a relatively slow area within the fast slab anomalies. This implies that, though mantle upwelling might be occurring in this area, the slab might just be weakened with fractured or faulted zones. We suggest that the origin of the weakened zone of the slab may be due to segmentation or fingering of the slab during subduction (Fig. 7b). Alternatively, it may have been weakened by mantle convection (Houseman and Molnar, 2001) or slab break-off of Greater Indian lithosphere (DeCelles, *et al.*, 2003). In response to the stresses caused by subduction and/or uplifting of the heated Indian slab, the fractured zone in the slab and over-pressure of the asthenospheric layer could produce seismic anisotropy observed over this area (McNamara, *et al.*, 1994). It is fortunate that previous geophysical and geochemical studies conducted within this anomalous area have the opportunity to observe the signature of the deep mantle. However, it is unfortunate that, if this anomaly truly exists, we cannot generalize the lithospheric structure beneath the Tibetan plateau based on findings in this area alone.
4.5 Inference for the cause of a destructive intraplate earthquake

The core of the Indian slab is a coherent high-velocity anomaly as thick as 200 km, such as that seen beneath northern India in cross section B-B1 in Fig. 4. The coherent high-velocity anomaly of the slab and its apparent bending far south of the Himalayan thrust front indicates that the slab is quite strong and rigid. An implication of this is that stress generated by the resistance to the subduction due to buoyancy of a heated slab can be carried along the slab.

The M$_w$7.5 destructive earthquake that occurred on 26/01/01 near Jamnagar, India, is located at the thinnest point of the high-velocity slab layer (Fig. 4, A-A1). The hypocenter of this intraplate earthquake is located at the position where the slab just starts to thicken northwards toward the subduction zone. The thinning of the slab at this location is partially due to the low-velocity anomaly that was interpreted as the signature of the Deccan plume (Kenneth and Widiyantoro, 1999). According to the USGS rapid moment tensor solution, the first focal plane of the double-couple solutions (292° strike, 36° dip, 136° slip) of this thrust event faces the direction of N22°E, which is parallel with cross section A-A1. Thus, we propose that this destructive earthquake is due to a failure of the Indian lithosphere at its weakest point in response to the stress originated from its subduction beneath Tibetan plateau.

5. Conclusions

Establishing the 3-D deep structure of the crust and mantle is key to understanding the formation of the Tibetan plateau. Our analysis of a high-resolution
global tomographic model indicates the existence of a high-velocity subducted Indian lithospheric slab beneath nearly the entire Tibetan plateau. These results, coupled with existing field-based crustal shortening estimates suggest that uplift of the Tibetan plateau was assisted by subhorizontal subduction of Indian lithosphere. In addition, a low-velocity asthenospheric layer might exist between the Tibetan lithosphere and the subducted Indian slab, though this notion is highly interpretive. The heating of the subducted continental slab and the presence of the overlying asthenospheric layer likely play a major role in the development and maintenance of the high elevation and flatness of the Tibetan plateau. Our interpretation is that, the uplift history and low relief of the Tibetan plateau is a result of subhorizontal subduction and heating of Indian lithosphere that is separated from Tibetan lithosphere by a thin channel of asthenosphere. Two predictions made by our model are: 1) the amount of shortening in the Himalayas is equivalent to the amount of underthrusted Indian mantle lithosphere and; 2) a young mantle geochemical signature should be present along the entire southern portion of the Tibetan plateau. The Tibetan crust is not completely cut off from mantle flows beneath the subducted slab. There is a large low-velocity anomaly north of the Indus-Yalu suture zone between 85ºE and 93ºE that extends from the crust all the way down to at least 310 km depth beneath the plateau. This low-velocity anomaly is indicative of mantle upwelling through a weakened zone of the subducted slab. Interestingly, many previous studies, including recent seismic array experiments, were conducted within this anomalous region. At its strongest core west of 85ºE, the Indian slab begins its downward bending hundreds of kilometers south of the Himalayas. Thus, the Indian slab is probably quite rigid and the stress caused by the resistance to the subduction could be
carried along the Indian slab. This scenario suggests that the destructive earthquake that occurred on 26/01/01, a thrust event located at the weakest point of the Indian slab, is likely a direct consequence of subduction of the Indian slab beneath Tibetan plateau.

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References


and Sr-Nd-Pb-O isotopic constraints for mantle source characteristics and petrogenesis. J. Petrol., 40 1399-1424.


Zhao, W. L., Morgan, W. J., 1987, Injection of Indian crust into Tibetan lower crust: A two-dimensional finite element model study. Tectonics 6, 489-504.


Figure Captions

Fig. 1. Map view of *P1200* tomographic model (Zhou, 1996) for Tibet region at depth range of 165-260 km. Red lines are major faults and red dotted lines are major suture zones in Tibet. IYSZ – Indus-Yalu suture zone; BNS – Bangong-Nujiang suture; JS – Jinsha suture. Purple crosses are earthquake foci. Purple star is the location of the destructive earthquake near Jamnagar, India, on 26/01/01. Dark gray curve delineates the inferred northern margin of the subducted Indian lithospheric slab in this depth range. Light gray curve outlines the high-velocity portion of the Tibetan lithospheric mantle above 120 km depth.

Fig. 2. Depth slices of velocity variations of the *P1200* model (Zhou, 1996). The coastline is shown in green, and 4-km elevation is shown in black. On the 75-120 km slice the high-velocity portion of the Tibetan lithospheric mantle is outlined by a shadowed light gray curve. On the 165-210 km and 210-260 km slices the inferred margin of the subducted Indian lithospheric mantle is indicated by a shadowed dark gray curve. Other legends follow that of Fig. 1.

Fig. 3. Result of checkerboard resolution tests at six depth ranges, as indicated in the lower-left corner of each panel. The lateral dimension of the impulses is 3°x3°.

Fig. 4. Four great-circle cross sections of P-wave lateral velocity variations at locations shown in the insert map. Small purple crosses are earthquake foci. The star in A-A1 denotes the destructive earthquake near Jamnagar, India. Shown above each section is topographic profile with a 20:1 vertical exaggeration. Dashed lines in magenta are elevations of 0, 2, and 4 km.

Fig. 5. Fourteen great-circle cross sections of P-wave lateral velocity variations at locations shown in the insert map. The lateral dimension is latitude for Sections E-E1 to O-O1, and longitude for Sections P-P1 to R-R1. See caption of Fig. 4 for other legends.

Fig. 6. Differential residual sphere predictions from the P1200 model for four events studied by Zhou et al. (1996). Each event pair is indicated below each sphere.
The differential traveltime residuals are plotted as a function of azimuth along the circumference and takeoff angle along the radius. The blue stars indicate relatively fast arrivals in sec, and the red crosses indicate relatively slow arrivals.

Fig. 7  a). Tectonic map of the Tibet-Himalaya collision zone modified from (Yin and Harrison, 2000).  b). Schematic Cross-section (A-A’) across Tibet-Himalayan orogen showing tectonic interpretation based on surface geology and tomography results from this study. Indian mantle lithosphere beneath central Tibet is interpreted to be underthrust at a steeper angle than in the western and eastern portions. AKMS – Ayimaqin-Kunlun Mutztagh suture, BNS – Bangong-Nujiang suture, IYS – Indus-Yalu suture, JS – Jinsha suture, MFT – Main Frontal thrust, MBT – Main Boundary thrust, MCT – Main Central thrust, STD – South Tibet detachment, GCT – Great Counter thrust, ATF – Altyn Tagh fault, LM – Lithospheric mantle

Fig. 8. Time required for a lithospheric slab to lose half of its initial temperature difference from that of ambient mantle, assuming thermal diffusivity $\kappa = 1\text{mm}^2\text{s}^{-1}$. 
Figures

Fig. 1
Fig. 5
Ev82/1/23 - Ev73/7/14

Ev82/1/23 - Ev73/9/8

Ev82/1/23 - Ev80/7/29

Ev80/7/29 - Ev73/7/14

Fig. 6
Fig. 8