Seismic P-wave tomography in eastern Tibet: Formation of the rifts

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For better studying the relationship between the rifts and deep structure, a detailed P-wave velocity structure under eastern Tibet has been modeled using 4767 arrival times from 169 teleseismic events recorded by 51 portable stations. In horizontal slices through the model, a prominent low-velocity anomaly was detected under the rifts from the surface to a depth of ~250 km; this extends to a depth of ~400 km in the vertical slice. This low-velocity anomaly is interpreted as an upper mantle upwelling. The observations made provide seismic evidence for the formation of north-south trending rifts. East of the low-velocity anomaly, a clear high-velocity anomaly is found between depths of 40 and 200 km. Due to its shallow depth, we suggest that it consists of materials from an ancient continental closure rather than the Indian Plate. From depths of 250 to 400 km, a high-velocity anomaly appears to the south of the Jiali Fault. This anomaly may correspond to the northern edge of the Indian Plate that detached from the surface under the Himalayan block. We suggest that the Indian Plate underthrusts no further than the Jiali Fault in eastern Tibet.

tomography, upper mantle upwelling, Indian plate subduction, north-south trending rifts, Tibetan Plateau

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The Tibetan Plateau is the world's highest altitude area and a very important region for the geosciences. Since the plateau was formed by the collision of the Indian and Eurasian plates about 50 Ma ago [1] and the subsequent post-collisional intra-continental deformation, strong structural distortion, lithospheric thickening, uplift of the plateau and development of the Himalayan mountains has occurred in this area. Although the Indus-Tsangpo, Bangong-Nujiang and Jinsha River sutures provide some evidence of Tethyan evolution, the precise relationships between the north-south trending structures of southern Tibet and the deep structure of the region are still not clear. Are they grabens [2] or deep fractures? Undoubtedly, these north-south trending structures are the most prominent surface feature in southern Tibet, but their formation mechanism and their relationships with shallow and deep structure [3] are not obvious. Resolving these problems will provide a way to better study

the formation and evolution of the Tibetan Plateau.

To study the uplift mechanism of the Tibetan Plateau, international exploration projects such as the INDEPTH, Hi-CLIMB and ANTILOPE projects have been undertaken. These projects have provided extensive seismic data sets that can be used to investigate deep structure in this area [4–7].

In the last 20 years, much seismic research has been carried out in the Tibetan Plateau facilitated by the rapid development of seismometer technology. Surface wave investigations suggest that the entire plateau is underlain by a relatively cold lithospheric mantle [8]. Applications of travel time techniques, Zhou [9] have shown that the Indian Plate underthrusts the whole plateau. Other research has found that relatively low S-wave velocities occur in the upper mantle of central and northern Tibet [10,11]. The work of Chen [12] supports the existence of strong radial anisotropy in most of Tibet because of the subduction of the Indian Plate under the Eurasian Plate. Using reflection seis-

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mology, Zhang [13,14] detected that the thickness of crust exhibits an east-west trending change at around 31.5°N , but there is no obvious variation at 29°N . Moreover, he considered that the angle of the Indian Plate varies from high to low while subducting.

These seismology projects were mostly established in southern and central Tibet; less investigation has occurred in eastern Tibet. Additionally, most seismometer deployments have trended north-south, which results in arrays that are not optimally oriented for travel time tomography investigations. In this study, a 3-D P-wave velocity structure model for the crust and upper mantle of southeastern Tibet is constructed using travel time data from 51 portable stations of the Namche Barwa Broadband Seismic Network. The result displays the relationship between deep structure and the rifts of southeastern Tibet, and reveals that the Indian Plate underthrusts no further than the Jiali Fault in this area.

1 Data and methods

In this study, 4767 P-wave arrival times were picked from original seismograms recorded by the densely distributed portable seismometers of the Namche Barwa Broadband Seismic Network, during 2003 and 2004 (Figure 1). The picking accuracy is estimated to be 0.2 to 0.4 s. To ensure the accuracy of the tomographic result, several rules have been considered in selecting data: (1) the magnitude is restricted to $M5.5$ or greater; (2) each event that includes more than 10 available records is taken into account; and (3) all events within an epicentral distance range of 30° – 90° are used.

The hypocenter information was provided by the United States Geological Survey and the layout of events used in this study is shown in Figure 2. We can see that most earthquakes used in this study occurred in the eastern part of the region and only a few events were located in the western part; this is further revealed in the ray distribution (Figure 3).

Figure 1 Map of the study region on the Tibetan Plateau. ITS denotes the Indus-Tsangpo suture; The triangles show the locations of the portable seismometers deployed in the study area. Insert map indicates the location of the study area.

Figure 2 Distribution of 169 teleseismic events (hollow circles) used in the study. The solid triangle corresponds to the center of the study area.

Although the rays on the eastern side intersect more than those on the western side, there are enough intersects in most parts of the study area.

In the tomographic method, travel time residuals, which are derived by subtracting theoretical travel times from observed travel times, are adopted in the inversion. Theoretical travel times were calculated by applying the IASP91 model [15] and the observed travel times are derived by subtracting the origin time from the observed arrival time. Absolute residuals are often used in regional and local travel time tomography. However, because all the ray paths are included in the model, the relocation of events is very important. By contrast, teleseismic tomography can neglect the process of relocation by adopting relative residuals, which are obtained by subtracting each event's mean residual from its absolute residuals.

We know that the Tibetan crust is very different from other regions in its thickness and lateral heterogeneity. To remove the effect of this special crust, an accurate crust correction [16] was performed.

After several checkerboard tests with different grid generations, the study area has been parameterized with an optimal grid mesh of $0.5^{\circ} \times 0.5^{\circ}$ laterally and 30 to 50 km vertically. The 3-D ray tracing technique can calculate ray paths efficiently and accurately. When the model contains structurally-complex velocity discontinuities, it is also powerful [17]. After ray tracing, the LSQR algorithm [18] with damping and smoothing parameters [19] was applied to invert the large and sparse observation matrix.

2 Results

A checkerboard test [20] has been conducted to measure the accuracy of the inversion results (Figure 4). In the checker-

Figure 3 Distribution of the 4767 rays used in this study in plain view (a) and vertical cross-section (b).

Figure 4 Checkerboard test. Red and blue denote low- and high-velocity perturbations, respectively. The velocity perturbation scale is shown in the bottom.

board image, we can see that the resolution is good in both plan (Figure 4(a)) and vertical (Figure 4(b)) sections, even with apparent “smearing” at a depth of about 400 km due to the bottom of the model.

A horizontal slice through the inverted results beneath southeastern Tibet is shown in Figure 5. Between depths of 40 and 70 km, the velocity anomaly shows a prominent east-west distribution. The position of the strong low-velocity anomaly is related to the rifts on the surface, and their orientations are almost the same (i.e. trending north-south). At a depth of 100 km, even though the east-west tendency is still obvious, the amplitude of the perturbation reduces. Between the depths of 150 and 200 km, the tendency of the velocity perturbation varies from east-west to north-south. A high-velocity anomaly dominates south of Jiali Fault, whereas a low-velocity anomaly

dominates in the north. From a depth of 250 km to the bottom, the north-south trending velocity anomaly distribution, which is separated by the Jiali Fault, becomes clearer; however, a high-velocity anomaly dominates to the south of Jiali Fault whereas low velocities appear in the north. Note that although the resolution at a depth of 400 km is poor, the central part of the model is still clear at this depth.

A vertical slice taken at 30°N (Figure 6) was chosen to detect the east-west trending variation beneath southeastern Tibet due to its better resolution (Figure 4). At around 92°E, a high-velocity anomaly exists between depths of 200 and 400 km. Also, a very strong low-velocity structure extends from the surface to a depth of 300 km, manifested as a low-velocity anomaly shaped like a tilted pillar. Above this low-velocity structure, obvious high-velocity materials exist.

Figure 5 Plan slices of P-wave velocity beneath the study area. Red and blue denote low- and high-velocity perturbations, respectively. The perturbation scale is shown at the bottom.

3 Discussion

Our results at shallow depths (40–70 km, Figure 5) are similar to some earlier geophysical work in the area. The Pn wave tomography [21] showed a clear low-velocity zone exists around 91°E. Regional tomographic results for China and surrounding regions [22] also show this low-velocity zone in the same position. These two results did not use the data from Namche Barwa, but they both found the low-velocity anomaly at almost the same position. Global tomographic imaging [23], which includes the Nameche Barwa dataset, shows a low-velocity zone extending from the surface to a depth of about 310 km. A surface wave study [24,25] also shows this phenomenon. In addition, a prominent high-velocity anomaly is detected to the east of the obvious low-velocity anomaly. Using travel time tomo-

graphic techniques in the same region, Li et al. [26] limited the underthrust of the Indian Plate to no further than 30°N. Furthermore, he pointed out that the underthrusting distance becomes shorter from west to east. Using the same data, Ren et al. [27] also detected this high-velocity anomaly and proposed that it represents the Indian Plate.

On the other hand, the high-velocity anomaly seen in our results at shallow depths (above 70 km) contrasts with a low-velocity anomaly seen in some shallow geophysical work in the same region. For example, Makovsky et al. [28] proposed concentrations of free aqueous-fluid in the Tibetan middle crust based on controlled-source seismic data. Using Rayleigh wave tomography and the same dataset as this study, Fu et al. [29] also did not find the high-velocity anomaly at shallower depths (above 40 km). Such interpretations are found in results from magnetotelluric [30,31] and

Figure 6 P-wave velocity slice along 30°N.

reflection seismic [13] surveys. Using a Rayleigh and Love wave tomographic technique, but with different data, Chen et al. [32] detected this strong low-velocity anomaly and agreed that fluid flow in the middle crust may exist here.

At depths between 70 and 200 km, our high-velocity result is consistent with Fu et al. [29]. However, both Fu et al. [29] and Kumar et al. [33] have suggested that this anomaly is the Asian Plate. Comparing our results with those of other earlier studies, there is no such high-velocity anomaly existing around 98°E [26]. In the east of southeastern Tibet, in the vicinity of the Longmen Fault, travel time tomography [34,35] did not support the subduction of the Asian lithosphere directly to eastern Tibet. Besides these, there are no other obvious high-velocity anomalies to the west of the low-velocity zone [22,26,36]. Thus we suggest that this high-velocity anomaly is not caused by Indian Plate subduction, but rather due to materials sinking during continental closure, which are then taken to the surface by mantle material upwelling. From 200 km to the bottom of the model, a high-velocity anomaly primarily appears to the south of the Jiali Fault and a low-velocity anomaly dominates to the north. Because of this, we suggest that the Indian Plate underthrusts no further than the Jiali Fault and then breaks off under the Himalayan block. In addition to this feature, although we cannot be certain that the Jiali Fault is the distinct velocity boundary above 100 km depth, it becomes clearer between depths of 150 and 400 km. The particular reason for this phenomenon calls for further study.

By applying the receiver function method, Singh et al. [37] suggested that the strong low-velocity anomaly is caused by the delamination of the Indian lithosphere into

the transition zone (beneath the 410 km discontinuity). The main reason for the formation of rifts in southeastern Tibet is mantle material upwelling as we discussed in this study. Moreover, the pattern of upwelling is not vertical, but tilted, similar to the deflected upwelling that has been detected under Iceland, Hawaii, and the Baikal region [36]. The range of the rifting in southeastern Tibet is relatively small compared with that of Baikal and lacks correlative studies, but we still prefer the interpretation of deflected upwelling due to the good resolution (Figure 4(b)), computer simulation results [38] and the value of V_p/V_s [27].

To the west of this low-velocity zone, a high-velocity anomaly is detected between depths of 100 and 400 km. The resolution of this region (92° to 94°E) is believable, despite boundary effects. We suggest that this high-velocity structure corresponds to the Indian Plate due to its location and comparison with previous results [5,26]. Moreover, we suggest that Indian Plate subduction induced mantle upwelling in this region.

In this study, our determination of the structure beneath the rifts in southeastern Tibet could only be made because of the location of the portable seismometers. To study the relationships further between the rifts in southeastern and southern Tibet, more portable stations will need to be established.

4 Conclusions

A detailed P-wave velocity structure model under eastern Tibet was built using travel times collected from portable stations in Namche Barwa. Above a depth of 100 km, the distribution of velocities shows a clear east-west trend. From 150 km to the bottom of the model at 400 km, this trend varies from east-west to south-north, separated by the Jiali Fault. In southeastern Tibet, the Indian Plate underthrusts not far beyond the Jiali Fault, with a depth range of 150 to 350 km, and breaks off beneath the Himalayan block. Low-velocity anomalies with amplitudes of 2% are revealed under the rifts at around 92°E. This low-velocity structure extends from the surface down to a depth of 400 km and tilts toward the east along the 30°N profile. We interpreted this as upper mantle upwelling, an observation that provides seismic evidence for the formation of the north-south trending rifts. The transverse flow of mantle material induces the pattern of deflected upwelling.

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