Vertical crustal motions across Eastern Tibet revealed by topography-dependent seismic tomography

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Using a topography-dependent tomographic scheme, the seismic velocity structure of the Eastern Tibetan Plateau, including the uplifted Longmenshan (LMS) orogenic belt, is accurately imaged in spite of the extreme topographic relief in the LMS region and thick sedimentary covers in the neighbouring Sichuan Basin. The obtained image shows a high-resolution upper crustal structure on a 500 km-long profile that is perpendicular to the LMS. The image clearly shows that the crystalline basement was uplifted within the LMS orogenic belt, and that the neighbouring Songpan-Ganzi Terrane was covered by a thick flysch belt, with evidence of near-surface thrust faults caused by convergence between Eastern Tibet and the Sichuan Basin. The indication that the lower crust beneath the LMS was folded and pushed upwards and the upper crust was removed by exhumation, supports the concept of a lower crustal channel flow beneath Eastern Tibet. The image also reveals that the destructive Wenchuan earthquake of year 2008 occurred in the upper crust, directly at the structural discontinuity between Eastern Tibet Plateau and the Sichuan Basin.

The collision between the Indian subcontinent and Asia in the late Eocene resulted in crustal thickening and the high elevation of the Tibetan Plateau¹–⁷. The eastward moving crust of the Tibetan Plateau was obstructed at the Longmenshan (LMS) orogenic belt by the rigid Sichuan Basin⁸,⁹. Thus, the LMS orogenic belt (Fig. 1) is the eastern margin of the Tibetan Plateau, and was uplifted by the extrusion of rigid crustal blocks along the left lateral strike-slip faults¹⁰.

This orogenic belt is characterised by a steep topographic gradient, as the elevation rises from ~500 m on the eastern part (the Sichuan Basin) to over 4 km in height on the western part (in Eastern Tibet) within a short horizontal distance of less than 50 km¹¹,¹². It has been speculated that the build-up of this orogenic belt experienced a two-phase growth during the Cenozoic⁵,¹²–¹⁶ and was a result of the eastward flow of the deep crustal viscous channel within Eastern Tibet⁵,¹⁴–¹⁸ or lithospheric thrust faulting with large amounts of slip¹⁹–²¹. Here, we present a high-resolution image of the upper crustal velocity structure that enables us to accurately evaluate these interpretations.

In this paper, using seismic refraction tomography results, we re-interpret a 500-km long deep seismic sounding (DSS) profile that traverses the LMS orogenic belt in a perpendicular manner²². In the tomographic inversion for reconstructing a velocity model with such a steep topographic relief, we adopted a topography-dependent scheme²³ which generates a uniform ray path distribution in the imaging area and, therefore, has a well-constrained upper crustal velocity model. Using this velocity model for geodynamic interpretation, we are able to understand not only how the Tibetan Plateau interacted with the Sichuan Basin locally at the LMS orogenic belt but we also, potentially, able to understand the tectonic mechanism of large earthquakes which occurred beneath the orogenic belt.

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The LMS orogenic belt is a part of the northeast-southwest trending seismic fault zone. The devastating Wenchuan earthquake (Ms 7.9, 12 May 2008) occurred right beneath the LMS orogenic belt. The two neighbouring regions of the LMS orogenic belt are the Songpan-Ganzi Terrane in the northwest, and the Sichuan Basin in the southeast. The former is a Triassic orogenic belt, and the latter is a stable craton covered by undeformed Mesozoic-Cenozoic sediments. Along the DSS profile from northwest to southeast, the Longriba Fault (in the interior of the Songpan-Ganzi Terrane), the LMS Fault Zone, and the Longquanshan Fault (in the Sichuan Basin) are distributed sequentially (Fig. 1a). Within the LMS orogenic belt, a distinguishing feature of the surface geology is the Precambrian metamorphic complexes which are widely distributed from the northeast to the southwest along the strike direction (Fig. 1b). In this study, we imaged the two-dimensional (2-D) DSS section across the most north-eastern complex, the Pengguan complex, which is assumed to have a high velocity in the near surface, relative to that in neighbouring regions.

Several DSS profiles have been previously studied for interpreting the upper crustal structure beneath Eastern Tibet and the Sichuan Basin. These studies approximated the abrupt topographic relief in the imaging process by simply filling in an artificial layer on the top to create a flat surface. This led to a lack of detail in the upper crustal models, as well as occasional inaccuracy. Only by taking into account the strong topographic variation in the seismic tomography can we obtain a high-resolution velocity model and, therefore, make a reliable interpretation of the upper crustal structure.

Data
Along the 500-km long DSS profile, 440 receivers (portable digital seismometers) were placed in order to record seismic data. These receivers were unevenly spaced at distance intervals within the range of 0.4 to 2 km (Fig. 1). Ten seismic shot records from the northwest to the southeast were selected for the tomographic analysis. They were spaced at distance intervals within the range of 10 to 80 km and labelled Sp1, Sp2, ..., Sp10 (Supplementary information). Within the LMS orogenic belt, shots and receivers were both placed more densely, enabling dense ray coverage beneath the target range. From these ten shot records, we picked a total of 569 first arrivals of refractive waves, propagated through the upper crust, within a maximum source-receiver offset of 140 km. Figure 2 depicts the traveltime-distance relationship for these first arrivals as black crosses. The relationship is summarised in what follows.

First, in the Songpan-Ganzi Terrane (profile distance 0–230 km) in the northwest, the diving wave within the sedimentary cover, Psed, was clearly presented within a source-receiver offset of less than 20 km. The apparent velocity of Psed was about 4.0–5.3 km/s, and the reduced traveltime was 0–0.8 s. The diving wave within the crystalline basement, Pg, followed the Psed and was recorded at the offset 20–140 km. This long observable offset (~140 km) indicates that there is no low-velocity layer in the upper crust. The apparent velocity of the Pg was about 5.8–6.3 km/s and hence the reduced traveltime was 0.8–1.0 s. The diving wave turning in the upper mantle, Pn, was difficult to discern due to the low signal-noise ratio at a long source-receiver offset.

Second, in the Sichuan Basin (profile distance 330–500 km) in the southeast, Psed was observed at a source-receiver offset of up to 50 km, longer than the maximum offset in the Songpan-Ganzi Terrane. The
The apparent velocity of Psed was 3.5–5.2 km/s and the reduced traveltime was 0–1.8 s. The Pg was traceable from the offset of 50 km to 100 km. Although the apparent velocity of the Pg was roughly the same as that in the Songpan-Ganzi Terrane, the reduced traveltime was 1.5–1.8 s. This indicates the existence of a relatively thicker sediment layer, sitting on top of the crystalline basement.

Third, at the LMS orogenic belt in the structural transfer zone (profile distance 230–330 km), there was no Psed but a strong Pg was observed. The apparent velocity of the Pg was the same as that in the neighbouring regions; however, the reduced traveltime was the lowest, at 0–0.7 s. This corresponds well to the high velocity in the crystalline basement outcrops.

In summary, these features of refraction waves clearly confirm the existence of the near-surface geological characteristics: a sedimentary cover in the Songpan-Ganzi Terrane, a high-velocity surface lithology and no sedimentary cover in the LMS orogenic belt, and thick sediment in the Sichuan Basin. These characteristics are confirmed by the high-resolution seismic tomography used in this study.

**Result**

The elevation of sources and receivers along the 500-km long DSS profile is variable from 4.2 km to 0.3 km. To take account of this strong elevation variation in the upper crustal model reconstruction, we used a topography-dependent tomography scheme in which grids conform to the curved boundary.

In this study, because of the irregular topography, only pseudo-orthogonal grids were defined in the tomographic inversion. These pseudo-orthogonal grids in the Cartesian coordinate were then transformed to a curvilinear coordinate. This transformation between two coordinates follows Poisson's equation. The traveltime equation, i.e., the eikonal equation, was also transformed to the curvilinear coordinate for calculating the first-arrival traveltime field. Given the traveltime field, traveltime gradients were computed spatially and ray paths were determined following the steepest gradient direction.

The inversion was carried out using a back-projection algorithm, in which traveltime residuals are uniformly projected along ray paths. The inversion procedure was stabilised by a smoothing operation, which controls the magnitude of the model update and spreads a time residual of a single ray path over a beam. Synthetic travel times that were calculated from the inverted velocity model matched well with the traveltimes that were picked from seismic data (Fig. 2). The root-mean-square traveltime residual was finally reduced to 0.11 s.

Topography-dependent tomography produced a high-resolution upper crustal velocity model (Fig. 3a), which is well-constrained according to the illumination of ray paths penetrating through the media (Fig. 3b). Beneath the Songpan-Ganzi Terrane, seismic rays reach a thickness of 9 km below the surface (depth from 4 km to −5 km). Beneath the LMS orogenic belt, the penetration depth is much shallower (about 6 km thick, depth from +2 km to −4 km), demonstrating the high velocity of the upper crust. However, beneath the Sichuan Basin, seismic rays reach down to a thickness of 12–15 km (depth from +1 km to −14 km).

In order to verify this upper crustal structure model, a joint inversion of the first-arrival times and reflection times, reflected from the intra-crustal interface, was conducted (Supplementary information). Figure 4 is the joint-inversion result and the ray paths in the final model. The penetration depth of the reflection ray paths is about 17 km. This updated velocity model confirms that the high-velocity anomaly is reliable at a depth greater than 5 km beneath the Longmenshan faults. The sub-vertically continuous high-velocity column and the uplifted interface beneath Longmenshan orogenic belt may be caused by the lower crustal extrusion.

**Discussion**

The high-resolution image of the upper crustal structure discloses significant features for each tectonic block: Thick sediments in the Sichuan Basin are juxtaposed against the thickened crust of Eastern Tibet, with compressional structure indicating the collision process.

The velocity model is consistent with the geological survey along the profile. Thick sediments in the Sichuan Basin are juxtaposed against the thickened crust of Eastern Tibet, with compressional structure indicating the collision process. Figure 5a plots a series of steeply dipping faults with relatively true dips which are deduced from the fold structure near the surface. Figure 5b shows that lateral velocity anomalies distributed in the upper crust correspond well with faults observed on the surface.
The Triassic flysch sediment in the Songpan-Ganzi Terrane is clearly imaged in Fig. 5b, and has a thickness of 8–9 km at the west end. Although the thickness of this sedimentary cover decreases generally from west to east, the undulating bottom interface of the low-velocity layer may be the response of fold deformations, caused by the upper crustal thrust-sheet34.

The thick stratified sedimentary cover in the Sichuan Basin has a thickness of about 10 km, and shows a clear horizontal structure. An important feature of this sediment cover is the transpressive structure in the western Sichuan Basin between the Jiangyou-Dujiangyan fault and the Longquanshan fault35, 36. This transpressive structure is caused mainly by lateral expansion and the gravitational effect of the thrust-sheet LMS. It may also have been reformulated subsequently by denudation37, 38, which is enhanced by abundant rainfall and abrupt topographic relief.

In contrast to the two neighbouring regions, there is no sediment covering the LMS orogenic belt, where the near-surface velocity value is as high as 5.6 km/s. This is consistent with the Pengguan complex distribution on the surface, and indicates the uplifted crystalline basement and subsequent denudation.

In the uplifting process of the LMS thrust-sheet belt, fault dislocation occurred repeatedly, inducing a large number of earthquakes. In Fig. 5b, epicentres within ±0.5 degrees are projected to the upper crustal structure model (China Earthquake Data Centre). Beneath the eastern half of the LMS orogenic belt, there is a rapid
velocity change in the horizontal direction. This rapid change corresponds well to the dense earthquake distribution within the belt.

Tectonic studies have postulated that crustal thickening caused eastward channel flow in mid- and lower crust of the Tibetan Plateau, which was obstructed by the lithosphere of the Sichuan Basin. This postulation has been verified by geophysical observations. Thermal and mechanical numerical models of deformation have demonstrated the upward expulsion of the Eastern Tibetan Plateau lower crust into the LMS orogenic belt with aggressive erosion. Our high-resolution velocity structure (Figs 3 and 4) provides strong confirmation of these speculations and numerical simulations on the extrusion of the lower crust beneath the LMS orogenic belt. In this paper, we construct a tectonic model (Fig. 5c) in which we interpret the high-velocity column beneath the LMS orogenic belt as an indication of the lower crustal expulsion. This extrusion contributes, either additively or dominantly, to the uplifting of the LMS orogenic belt. We also interpret that the lower crustal folding due to the obstruction of the Sichuan Basin lithosphere was the prime cause of the destructive Wenchuan earthquake in 2008.

Conclusions

Topography-dependent seismic tomography produced a high-resolution image of the upper crustal structure of the Eastern Tibetan Plateau. The image shows that the collision between the Tibetan Plateau and the Sichuan Basin compressed the upper crust along the profile, and that the fact of LMS orogenic belt being uplifted and tilted westwards led to the thickening of flysch sediment of the Songpan-Ganzi Terrane in a direction from southeast to northwest. Whereas the sedimentary cover in the Songpan-Ganzi Terrane was folded, the sediment of the Sichuan Basin clearly shows a transpressive structure. The lower crust was pushed upwards and exhumed by erosion at the LMS orogenic belt. This interpretation supports the concept of a lower crustal channel flow beneath Tibet. The image also indicates that the site of the destructive Wenchuan earthquake is directly at the upper crustal discontinuity between Eastern Tibet and the Sichuan Basin. Therefore, the high-resolution image of the upper crustal structure confirms the surface observations and geodynamic speculations of the Eastern Tibetan Plateau.

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Acknowledgements
Thanks go to the Geophysical Exploration Centre of the Chinese Earthquake Administration (CEA) for data acquisition in 2010. Thanks also go to the CEA (grant no. 201408023) and National Natural Science Foundation of China (grant nos 41604075, 41574092, 41430213, 41474111 and 41374062) for supporting this work.

Author Contributions
X.Z. initiated the analysis and prepared context figures. Y.W. focused on writing and finalised the paper. R.G. and Q.L. designed and oversaw the project. X.Z., Z.B. and T.X. performed the inversions and prepared...
figures displaying results. Z.B. and X.T. conducted data processing and geodynamic interpretation. All authors contributed to interpretation and revise the paper.

Additional Information
Supplementary information accompanies this paper at doi:10.1038/s41598-017-03578-z

Competing Interests: The authors declare that they have no competing interests.

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Supplementary information

Vertical crustal motions across Eastern Tibet revealed by topography-dependent seismic tomography, by X. Zhang, Y. Wang, R. Gao, T. Xu, Z. Bai, X. Tian & Q. Li

S1. Detailed parameters of each shot record

Ten seismic shot records were selected for analysis. They were spaced at distance intervals in the range of 10 to 80 km and labelled Sp1, Sp2, ..., Sp10 from the northwest to the southeast. Fig. S1 displays these ten shot records, marked with the first refraction phases.

The following table lists detailed coordinates and elevations of all ten shots:

| Shot Number | Longitude (E)       | Latitude (N)       | Elevation (m) | Shot charge (kg) | Number of wells | Depth of well (m) |
|-------------|---------------------|--------------------|---------------|------------------|-----------------|-------------------|
| 1           | 101°48.8226'        | 32°55.1377'        | 3468          | 2814             | 1               | 42.5              |
| 2           | 102°24.2320'        | 32°24.7443'        | 3596          | 2688             | 3               | 20.8              |
| 3           | 103°48.1650'        | 31°47.4255'        | 1712          | 600              | 2               | 26.5              |
| 4           | 104°03.2060'        | 31°35.8650'        | 1310          | 1000             | 1               | 10                |
| 5           | 104°10.3488'        | 31°27.6445'        | 688           | 600              | 1               | 35                |
| 6           | 104°18.4311'        | 31°23.2383'        | 486           | 800              | 2               | 20                |
| 7           | 104°24.2546'        | 31°18.9301'        | 530           | 1000             | 1               | 47.5              |
| 8           | 104°33.0524'        | 31°11.0742'        | 465           | 500              | 1               | 49                |
| 9           | 104°46.7510'        | 31°00.6347'        | 419           | 800              | 1               | 58                |
| 10          | 105°30.0357'        | 30°36.8452'        | 280           | 1800             | 1               | 61                |

Before the data acquisition, all seismometers underwent consistency verification to make sure that all of them could record a wide-angle event simultaneously. During the field experiment, all explosions and recorders were synchronised with GPS time. The sampling rate was 5 ms, and hence the time error between any seismometers is less than 5 ms.

S2. Resolution analysis of topography-dependent traveltime tomography

In this paper, traveltime tomography is carried out by using a back-projection algorithm. The initial velocity model is a 1-D function of depth, between depths 5 km and ~15 km. The velocity is increased linearly from 4.0 to 6.5 km/s. The velocity model is updated via iteration. The final velocity model is the output after 19 iterations. Although the RMS traveltime residual is initially about 1.1 s, it has been decreased steadily to 0.09 s through the iterative inversion.

To confirm the main features of the tomographic result, we have conducted two kinds
of resolution analyses, for the topography-dependent traveltime tomography (TDTT) solver.

(continues)
Figure S1. Ten shot records along the profile. Traces are normalised and bandpass-filtered (1–10 Hz). They are displayed with a reduced velocity of 6.0 km/s.

First, we apply a checkerboard test to evaluate the resolution as per similar observation surveys. We add alternate high and low velocity anomalies on the obtained tomographic velocity model. The velocity anomalies are described by formula $0.3 \times \sin(x) \times$
sinz (km/s), and with a space scale of 30 km (horizontal) × 15 km (vertical). When we invert the synthetic data, which are calculated from the checkerboard model, we apply the tomographic model (Fig.3a) as the initial model, and use the TDTT scheme. Comparison between the theoretical and recovered velocity anomalies, as shown in Fig. S2, indicates that the checkerboard pattern is well recovered along the wide-angle profile, which shows a high resolution of the data and scheme.

Figure S2. Checkerboard resolution test. The space scale of velocity perturbation is 30 × 15 km, and the value scale is shown at the bottom. Black stars on the surface denote shot positions.

The second resolution analysis is a restoring resolution test. In this test, we add a random Gaussian noise with a standard deviation of $\sigma = 0.2$ s to the synthetic data. The result, as shown in Fig. S3, illustrates the same zoning characteristics as with the tomographic result. It suggests that the main features of the tomographic imaging (Fig. 3a) are reliable. In fact, more specific features of upper crust are disclosed by our model, and thus more geodynamic information is revealed from our tomographic result.

S3. Comparison to the model expansion method

In this paper, we use the topography-dependent traveltime tomography (TDTT) scheme\textsuperscript{1,2}. It is in contrast to a model expansion scheme\textsuperscript{3} which uses the stair-steps approximate of the irregular surface and covers the top with a low-velocity layer that has an artificially-flat plane surface. However, this conventional scheme would cause not only accuracy loss but even also image distortion.

Fig. S4a is the velocity model that is obtained by the conventional scheme, which fills the top layer with an artificial medium having a low velocity of 0.5 km/s. In general, this model and that obtained from TDTT (Fig. 3a) have a similar main feature, and a small difference between them. We have seen uniformly distributed ray paths in the TDTT model, a key element for TDTT to have a high resolution. But, in the result obtained by
using the conventional method, there are messy rays and false rays above the surface, due to low-velocity filling (Fig. S4b).

In the Songpan-Ganzi terrane, the undulating sedimentary interface has not been clearly imaged, which may result from false rays shooting across the surface to the low-velocity filling. Moreover, the high-velocity anomalies (6.3 km/s) that are distributed in the depth range of 5–10 km may be artefacts that are also caused by erroneous ray distribution, which cannot be interpreted geologically.

Within the Sichuan basin, the velocity contours are more chaotic in the conventional result, which is inconsistent with the stable sedimentary environment of the Sichuan basin. Moreover, no compression-torsion can be interpreted from the velocity structure that was obtained by the conventional Hole’s method.

In the LMS fault zone, the uplifted basement cannot be clearly observed in this segment of profile. There is only a high velocity anomaly that is distributed beneath the LMS fault belt, with no outcrop on the surface, which is inconsistent with the severe denudation and the Pengguan complex that is distributed on the surface.

In summary, the velocity model that was reconstructed with the TDTT method has a clear and high-resolution image, and discloses significant features for each tectonic block, differing from the result obtained by the Hole’s method.

Figure S3. Restoring resolution test. (a) The final inversed model. (b) Restoring resolution test by adding random Gaussian noise (σ = 0.2 s) to the synthetic data from the final inverted model (a), and reconstructed using the TDTT solver.
S4. Joint inversion of the first-arrival times and a reflection times

In order to verify this upper crustal structure model, we have conducted a joint inversion of the first-arrival times and reflection times. We picked a reflection phase on the seismic records, which presumably is reflected from the intra-crustal interface. This reflection phase is labelled as P2, as shown in Fig. S5 for shot no. 2 and 6.

We have implemented the joint inversion of the first arrival (Pg) and the reflected arrival (P2) times. A grid size of 501×26 with a horizontal and vertical spacing of 1 km was employed in order to parameterise the model. In the joint inversion, the initial model was constructed based on the upper crustal model that was obtained by the Pg arrival time inversion (Fig. 3a). Fig. 4 (in main text) is the upper crustal structure that was obtained by this joint inversion. The final root-mean-square residual is reduced to 0.12 s and 0.16 s, for Pg and P2 respectively, suggesting a satisfactory convergence level.

The averaged depth of the reflection interface is approximately 17 km. The updated velocity model confirms that the high-velocity anomaly is reliable at a depth greater than 5 km beneath the Longmenshan faults. More importantly, it supports the crustal-scale interpretive model.
Figure S5. Picked Pg and P2 phases along the seismic records of shot no. 2 and 6, respectively.

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