Journal of Earth Science, *Vol. 20*, *No. 2*, *p. 438–447*, *April 2009* *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-009-0036-x

Test of Deep Seismic Reflection Profiling across Central Uplift of Qiangtang Terrane in Tibetan Plateau

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ABSTRACT: A test of deep seismic reflection profiling across the central uplift or metamorphic belt of the Qiangtang (羌塘) terrane, Tibetan plateau, provides a first image of the crustal structure. Complex reflection patterns in the upper crust are interpreted as a series of folds and thrusts, and bivergent reflections in the lower crust may represent a convergence between the Indian and the Eurasian plates.
KEY WORDS: Qiangtang terrane, central uplift zone, crustal structure, test of deep reflection profiling, convergent process.

INTRODUCTION

The Qiangtang terrane is located in the interior of the Qinghai-Tibet plateau between the Jinsha suture and the Bangong-Nujiang suture (Yin and Harrison, 2000; Fig. 1). Much attention has been paid to the lithosphere structure of the Qiangtang terrane. Many studies have shown that the Qiangtang terrane has a crustal thickness of 60–70 km, has an unusually hot and weak lower crust (Klemperer, 2006; Gao et al., 2005) and lies above the region where the Indian plate and the Eurasian plate converge in the depths of the upper mantle (Zheng et al., 2007; Kumar et al., 2006; Kosarev et al., 1999; Owens and Zandt, 1997).

The complex geology and geomorphology character in the Central Qiangtang terrane may be a response to the convergence and interaction of the plates at the present day, or in part to a geologic history dating back at least to the Triassic (Klemperer, 2008; Li et al., 2008; Bendick and Flesch, 2007; Yin and Harrison, 2000).

The Qiangtang terrane is dominated by the Cenozoic/Quaternary strata and widespread marine Jurassic deposits (Wang J et al., 2004; Wang C S et al., 2001; Zhao et al., 2000a, b). Older metamorphic rocks are exposed in the "Qiangtang metamorphic belt" or the "central uplift zone" (Kapp et al., 2003; Li et al., 1995). Li et al. (1995) interpreted the "central uplift zone" as a mélange belt along a paleo-Tethyan suture

This study was financially supported by the National Natural Science Foundation of China (Nos. 40830316, 40874045 and 40704016), the Ministry of Science and Technology of China (Nos. SinoProbe-02, 2006DFA21340), the Ministry of Land and Resources of China (Nos. 2004-06, 200811021), and the Open Fund of Key Laboratory of Geo-detection of China University of Geosciences (Beijing) (No. GDL0603).
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Manuscript received November 25, 2008.
Manuscript accepted January 28, 2009.

that closed in the Late Permian. Kapp et al. (2003, 2000) concluded that the central uplift zone was formed during Middle Triassic continental collision and exhumed during Late Triassic core-complex type extension. Wang C S et al. (2001) considered the belt as a result of the Late Paleozoic rifting. These different scenarios imply important distinctions about the early history of the Tibet plateau.

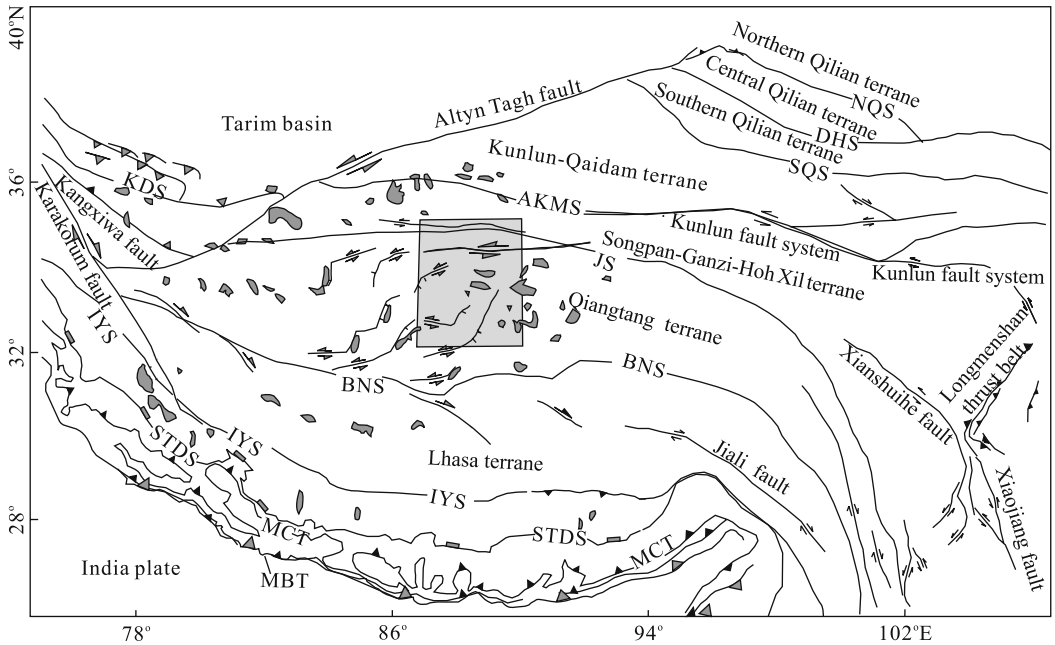

Figure 1. Sketch map showing the location of the Qiangtang terrane and the study area (after Yin and Harrison, 2000). IYS. Indus-Yarlung Zangbo suture; BNS. Bangong-Nujiang suture; JS. Jinsha River suture; AKMS. A'nemaqen-Kunlun-Mutztagh suture; SQS. South Qilian suture; DHS. Danghenanshan suture; NQS. North Qilian suture; KDS. Kudi suture; STDS. South Tibet detachment system; MCT. main central thrust; MBT. main boundary thrust.

Geophysical methods can image the deep structure of the Qiangtang terrane in order to understand its formation and evolution. Deep seismic reflection profiling is recognized internationally as the highest resolution probe of the crustal structure (Leven et al., 1990; Matthews and Smith, 1987; Barazangi and Brown, 1986). Deep seismic reflection profiling in the Tibetan plateau also revealed many of deep processes in the convergent orogenesis and plateau formation (Wang et al., 2007; Gao et al., 2006a, b, 2001, 2000; Ross et al., 2004; Zhao et al., 1997; Brown et al., 1996; Nelson et al., 1996).

Due to the difficult environmental conditions, it is very difficult to carry out deep seismic reflection profiling in the Tibetan plateau, leading to limited application of this methodology (Gao et al., 2005). The only previously published deep reflection profiles from Qiangtang are two test segments, only 10 km in length, near Duoma and Shuanghu (Ross et al., 2004). In order to study the deep structure of the Qiangtang terrane, from 2007 to 2008, with funding from the National Natural Science Foundation, the Ministry of Science and Technology, and the Ministry of Land and Resources of China, we acquired two deep seismic reflection profiles across the central uplift area and obtained details of the deep structure of the central uplift for the first time, thereby providing new data on the formation and character of the Qiangtang terrane.

DATA ACQUISITION AND PROCESSING

We carried out two test profiles in 2007 (named QT07) and 2008 (named QT08), totaling about 110 km of data, west of Shuanghu. Profile QT07 crosses the north part of the central uplift in a northeast-southwest transect, from west of Amucuo (Lake) to the south of Kongkongchaka Lake. Profe QT08 intersects the southern end of the QT07 line, and continues south on the east side of Beileicuo (Fig. 2).

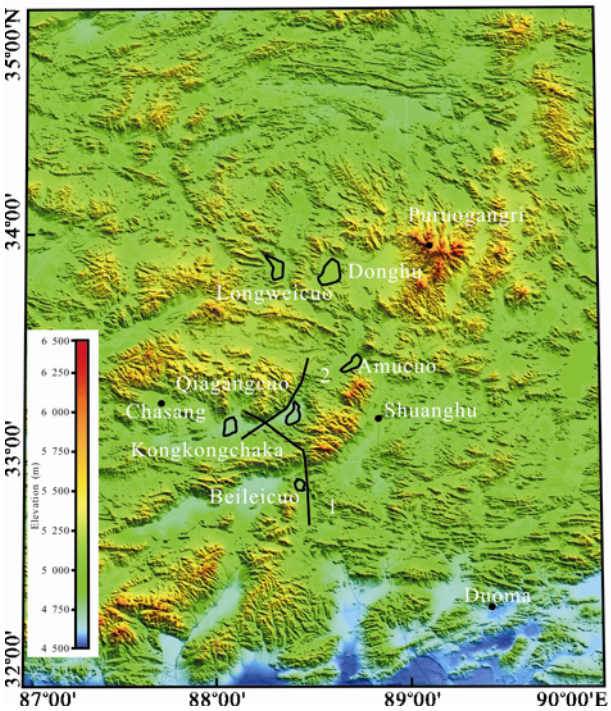

Figure 2. Sketch map showing the location of the deep seismic profiles. 1. QT08 line; 2. QT07 line. Base map is from http://www. globalmapper. com.

Our seismic reflection sections are common depth point (CDP) stack profiles. The data acquisition systems used were Sercel 408XL for QT07 and Sercel 428XL for QT08, using a preamplifier gain of 12dB to record 720–1 000 channels at a sample rate of 2 ms for a record length of 30 s. A linear array of SM-24 super receivers was used with a group interval of 40 m. Small explosive charges of 16–20 kg were detonated in shot-holes drilled to a depth of 18–20 m and spaced at 160 m (QT07) or 120 m (QT08) using a split-spread configuration with a minimum source-receiver offset of 20 m. Larger shot sizes were used to enhance deep penetration, with a 96 kg charge every 5 km and big shots of 200–400 kg fired in the center and at the ends of each profile, and recorded by the whole spread.

Data processing include editing of bad traces, refraction statics, true amplitude restoration, denoising, surface-consistent amplitude compensation, surface-consistent deconvolution, velocity analysis, residual statics, normal moveout, stack, and display. In order to address highly variable elevations and near-surface conditions, we used broad-exchange refraction static method to do primary field static correction, surface-consistent amplitude compensation technology to remove energy difference between different seismic sources and receivers and to balance amplitudes, adaptive surface-wave attenuation to remove surface waves, and frequency-division noise suppression to eliminate high-energy interference, without significant loss of the reflected-wave components. None of the reflection sections shown in this article are migrated; that is, the true structural location of all reflectors will lie somewhat up-dip of, and be steeper than, shown in these unmigrated profiles.

DATA DESCRIPTION: MAIN FEATURES OF REFLECTION PROFILES

With careful data acquisition and processing, we have obtained seismic reflection profiles with a reasonable signal-to-noise ratio, allowing us to study the deep structure of the central uplift.

Reflection of Volcanic Rocks

In the middle and northern parts of the QT07 section, from CDPs 1501 to 301, there are weak and disrupted reflections, perhaps corresponding to volcanic rocks of the central uplift.

Volcanic rocks thrust on the north side to the deep depression above. In the lower part of these volcanic rocks at 2.0 s TWT (two-way time) behave a group of reflections that can be tracked continuously, which could possibly be the surface between the volcanic rocks and the lower beds (Fig. 3a).

Reflections from Cenozoic sedimentary rocks

In the shallowest part of the southern end of QT08 (roughly at 0–1 s TWT), from CDPs 4051 to 3751, we see the highest amplitude and most coherent reflections on our profiles, presumably representing Cenozoic sedimentary strata on the southern edge of the central uplift (Fig. 4a).

Reflection of concealed uplift in the upper crust

In the middle of the QT07 section, there is a clear upward-convex reflection (CDPs 1951–601) spanning nearly 30 km; from 2.5 s to 5.0 s TWT, with asymmetrical flanks dipping steeply southward and gently northward. We suggest that this arch respresents the Paleozoic uplift (Fig. 3b).

Reflection of crystalline basements

Both the QT07 and the QT08 profiles show strong reflections, sub-horizontal and at a consistent in time of 5.0–6.5 s TWT. Combined with the previous interpretation of the results of seismic profiles (Lu et al., 2006), we believe that this may be the crystalline basements of the Qiangtang terrane (Figs. 3c1, 3c2, and 4b).

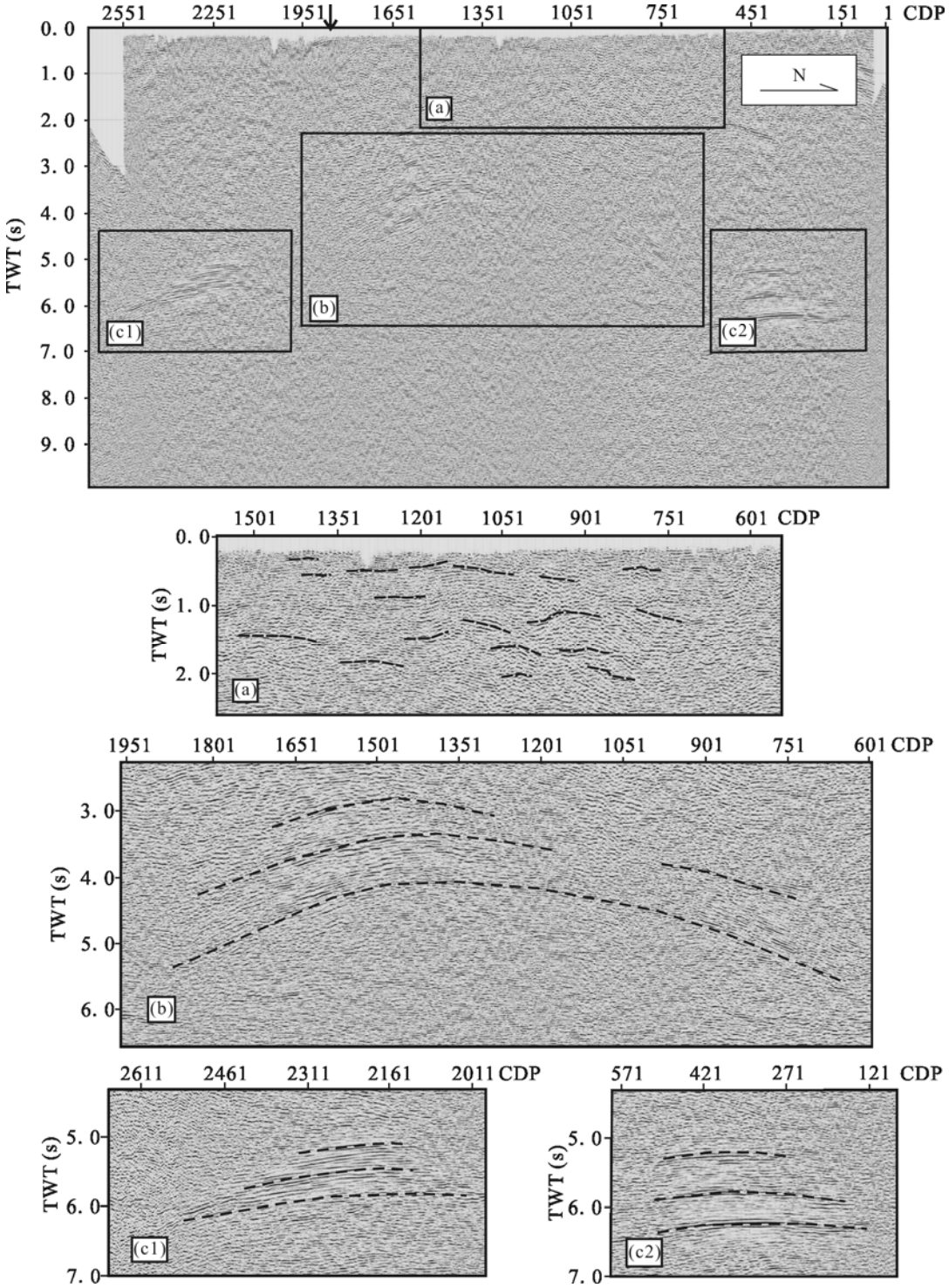

Figure 3. Reflection characters of the upper crust of the QT07 section in the central uplift, Qiangtang terrane. CDP spacing is 20 m, ↓. the location of the intersection with QT08, the horizontal exaggerations for the whole profile and for the small sections are 1 : 1 and 1.2 : 1, separately. (a) Reflections from volcanic rocks; (b) strongly reflective arch; (c) intra-basement reflections.

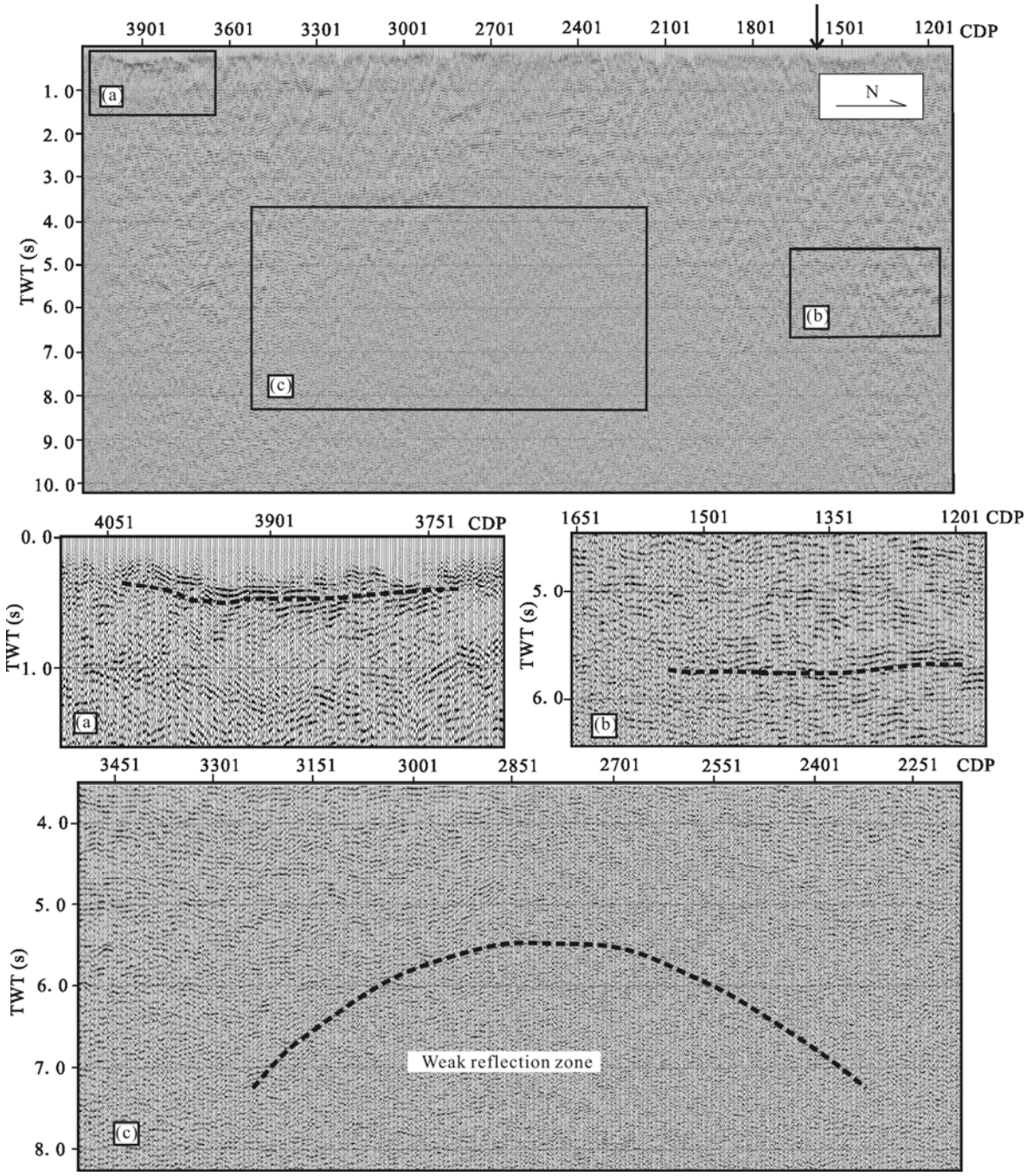

Figure 4. Reflection characters of the upper crust of the QT08 section in the central uplift, Qiangtang terrane. CDP spacing is 20 m, ↓ is the location of the intersection with QT07, the horizontal exaggerations for the whole profile and for the small sections are 1 : 1 and 1.2 : 1, respectively. (a) Sedimentary reflections; (b) intra-basement reflections; (c) poorly-reflective zone in the upper crust.

Non-reflective zone in the upper crust

In the middle of the QT08 profile, in the southern part of the central uplift, a region of weak or absent reflections is evident beneath 5.5 s TWT in the range of CDPs 3301–2251, spanning 20 km; this structure is quite different from the QT07 section (Fig. 4c).

Reflection Character of the Lower Crust

Our deep seismic reflection profiles show that ubiquitous dipping reflections are the most obvious features in the lower crust under the central uplift of the Qiangtang terrane. Figures 5a and 5b show the north-dipping reflections in the lower crust of the QT07 and QT08 profiles, which occur below 10 s

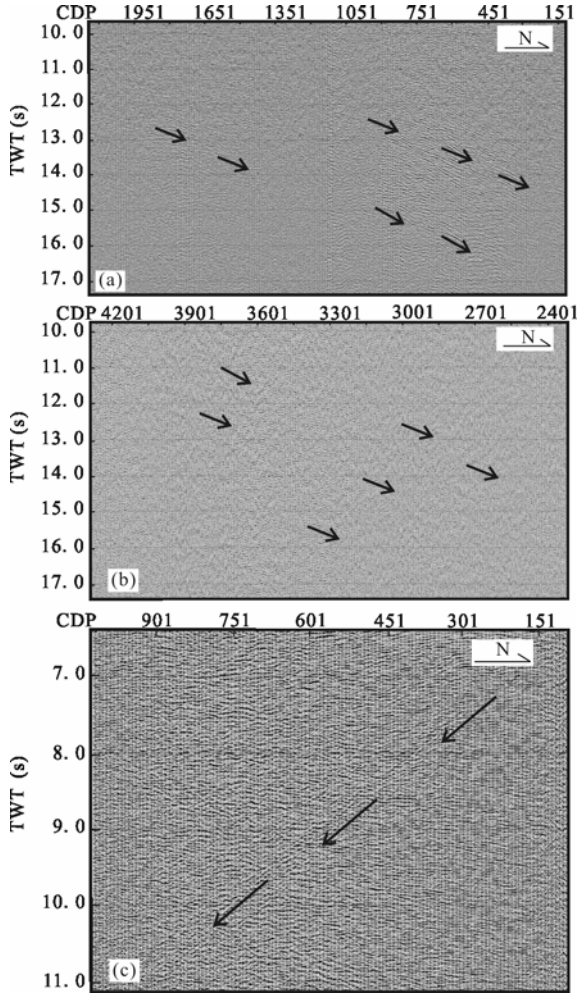

Figure 5. Dipping reflections in the lower crust of the central uplift, Qiangtang terrane. (a) The north-dipping reflections in the lower crust of the north part of the central uplift (QT07 line); (b) the north-dipping reflections in the lower crust of the south part of the central uplift (QT08 line); (c) the south-dipping reflections in the lower crust of the north part of the central uplift (QT07 line). These sections have the same horizontal exaggeration of 1 : 1.

TWT (30 km depth) and mostly extend to 17 s TWT and even deeper (below 50 km).

At the northern end of the QT07 profile, south-dipping reflections occur from 6 to 12 s TWT, above the even deeper north-dipping reflections (as shown in Fig. 5c). This group of reflections, spanning 12 km, when taken with the deeper north-dipping reflections (as shown in Fig. 5a), forms a "crocodile" structure in the middle-to-lower crust.

CRUSTAL-SCALE IMAGE AND PRELIMINARY INTERPRETATION OF THE CENTRAL UPLIFT IN QIANGTANG TERRANE

Linking the QT07 and QT08 at their intersection, we created a single long profile spanning the central uplift (Figs. 6 and 7). We interpret a series of north-directed thrusts in the upper 10 km. Qiangtang metamorphic basement is presumably represented by the deeper layered and arched reflections down to 6.5 s TWT, or 18 km. At 22 s TWT, we find a group of reflections with variable character and energy, being also the deepest reflections observed in most cases. In combination with other research findings (Tilmann et al., 2003; Zhao et al., 2001), we conclude that the Moho reflection is at a depth of 66–68 km (calculated assuming an average crustal velocity of 6.0–6.2 km/s, Haines et al., 2003).

The north and south of the intersection point of the central uplift show some differences in the upper crust structure (down to 6.5 s TWT, 19 km depth). The obvious strong basement reflections in the north, both the upper-crustal arch and the mid-crustal south-dipping reflections, contrast with the non-reflective region in the south. These differences in deep structure suggest an important boundary in the upper crust. The north-dipping reflectivity in the lower crust below 8 s TWT may be due to a long-range influence of the Indian plate as it subducted northward beneath the Qiangtang terrane. Because no such large-scale north-dipping reflections have been found in the upper crust of the Qiangtang terrane, we conclude that this effect of northward subduction exists only in the lower crust, perhaps due to material flow in the weak lower crust of the Tibetan plateau, or to the northward limit of the Lhasa block beneath the central uplift (Klemperer, 2008; Haines et al., 2003).

In contrast, in the northern part of the central uplift, south-dipping reflections occur from 6 to 12 s TWT, spanning the northern 12 km of our profile. Near the Moho, more south-dipping reflections are seen, but are weaker in energy (Fig. 7). We do not believe that these south-dipping reflections are an "edge" effect due to the short length of our profile, because their continuity is clear (Fig. 5c). We may surmise that, by analogy with the north-dipping reflections to the south, the south-dipping reflections in

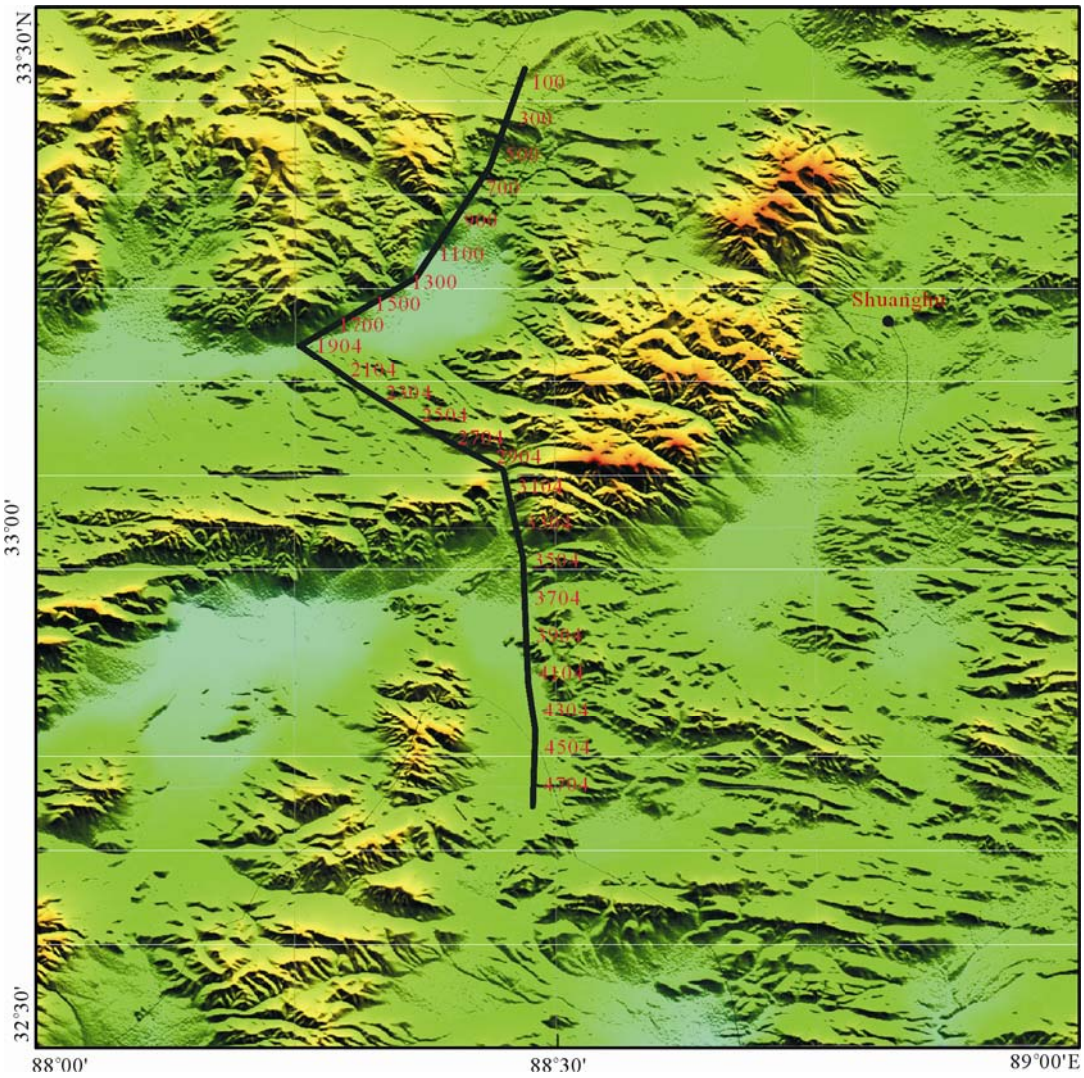

Figure 6. Sketch map showing the location of the combined deep seismic reflection profile.

the north are related to the southward subduction of the Eurasian plate (Shi et al., 2004; Kind et al., 2002). This interpretation would imply that the central uplift of the Qiangtang terrane is located at the location where the two large plates (India and Eurasia) interact most strongly. Alternately, the south-dipping reflections, and the "crocodile" structure they make with respect to the deeper north-dipping reflections may be regarded due to bivergent thrusting within a single subduction episode (Meissner et al., 1991; BABEL Working Group, 1990).

CONCLUSIONS

(1) The crystalline basement in the Qiangtang terrane has been imaged down to 5.0–6.5 s TWT on our reflection seismic profiles.

(2) The shallow part of the upper crust is dominated by northward-directed thrusting.

(3) The southern and northern parts of the Qiangtang terrane show different upper-crustal structures.

(4) The lower crust under the central uplift shows mainly north-dipping reflections but also shows some south-dipping reflections in the northern limit of our seismic profile. These north- and south- dipping reflections represent a "bivergent" structure in the northern part of the central uplift. These bivergent reflections in the lower crust imaged the style and process of convergence between the Indian and the Eurasian plates.

ACKNOWLEDGMENTS

We wish to thank Wang Jian, Tan Fuwen, Xiao Xuchang, Li Cai, Wang Chengshan for their helpful

discussion on the geologic problems of the Qiangtang

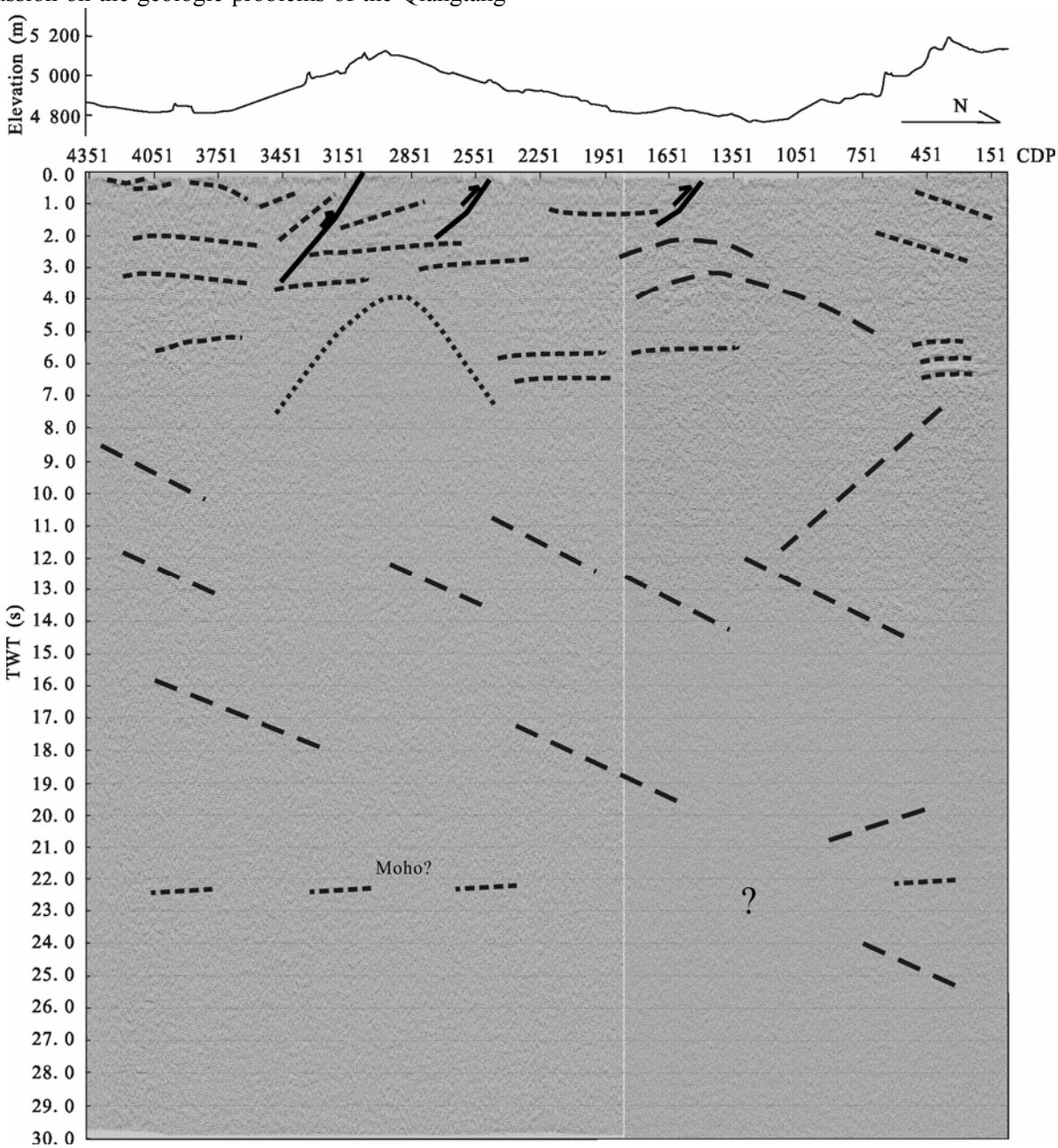

Figure 7. Preliminary interpretation of the combined deep seismic reflection profile across the central uplift.

terrane. In particular, Wang Jian and Tan Fuwen provided much help in choosing the profile locations and in collecting additional geological data.

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