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Cenozoic thrust system, basin evolution, and uplift of the Tanggula Range in the Tuotuohe region, central Tibet

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ABSTRACT

New field mapping reveals a large Cenozoic thrust system in the Tanggula Range and Tuotuohe region, central Tibet. The thrust system is parallel to the Tanggula Range, and it is termed the Tanggula thrust system (TTS). Three thrust belts can be identified in this thrust system. From south to north, they are the Geraddong-Esuima thrust belt (GEB), the Quemocuo-Gaina fold-thrust belt (QGB), and the Baqing-Wulwl thrust belt (BWLB). The deformation styles can be classified as high-angle imbricate thrust, fold thrust and lower-angle imbricate thrust, respectively. The initiation of sedimentation in the Tuotuohe Basin and stratigraphic unconformities indicate that the thrust system was developed during 52–23 Ma. Sequential filling patterns, sedimentary facies and paleocurrents indicate that the Tuotuohe Basin was a foreland basin in front of the TTS. Restored structural sections suggest 89 km (60%) of N–S shortening in the TTS and 96 km (48%) shortening in the Tuotuohe Basin. The thrust system has not only influenced the development of this Cenozoic basin, but also resulted in the rapid uplift of the Tanggula Range during the Eocene and Oligocene.

1. Introduction

The Indo-Asian collision and associated intracontinental deformation have resulted in large-scale crustal shortening and uplift of the Tibetan Plateau (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Achache et al., 1984; Allègre et al., 1984; Besse et al., 1984; Patriat and Achache, 1984; Dewey et al., 1988; Harrison et al., 1992; Pichon et al., 1992; Ratschbacher et al., 1994; DeCelles et al., 1998; Yin and Harrison, 2000; DeCelles et al., 2002; Wang et al., 2002, 2008; Aitchison et al., 2011; Zhang et al., 2011). In past decades, much attention was focused on determining the spatial and temporal distribution of the deformation, crustal shortening and uplift of the plateau.

Previous studies have confirmed that several thrust systems exist between the southern Himalayan and northern Qilian regions, including the Main Boundary thrust (MBT), Main Central thrust (MCT), Great Counter thrust (GCT), Gangdese thrust (GTS), Shiquanhe–Gaize–Amdo thrust (SGA), Western Kunlun thrust belt (WKT), Northern Kunlun thrust belt (NKT), Nashan thrust (NST), and North Qilian thrust belt (NQT) (Fig. 1A; Schelling, 1992; Srivastava and Mitra, 1994; Ratschbacher et al., 1994; Yin et al., 1994, 1999; Kapp et al., 2003; Rumelhart et al., 1999). Sedimentation and thermal history studies suggested that the thrust systems not only contributed to the crustal shortening, but also led to the tectonic uplift of the adjoining mountains and the development of sedimentary basins (Li et al., 1979; Allègre et al., 1984; Dewey et al., 1988; Rumelhart, 1998; DeCelles et al., 2001, 2002; Wang et al., 2002, 2003; Zhu et al., 2006; Wang et al., 2008; Yin et al., 2008).

Compared with the Himalayan, Lhasa, and Qiliangshan terranes, little is known about the Cenozoic thrusting and crustal shortening in the Qiangtang terrane. The Tuotuohe region of the North Qiangtang terrane is an ideal location for studying Cenozoic deformation and basin development, due to the Tanggula Range and the Hoh Xil Basin (HXB) that are both present in this area (Fig. 1A, B). Previous investigations revealed that this region has undergone intense deformation during the Cenozoic (Leeder et al., 1988; Yin and Harrison, 2000; Wang et al., 2002), and the formation of the Hoh Xil Basin was facilitated by the early Tertiary thrusting (Liu and Wang, 2001; Wang et al., 2002). Moreover, it is conceivable that the Hoh Xil and Qaidam basins (QB) may be the same basin, and both are constrained by the Cenozoic thrusting (Yin et al., 2008). However, little is known about the relationships of the Cenozoic thrusting, basin evolution, and uplift of the Tanggula Range because of the harsh working conditions and limited geological investigations in this region.

To unravel the spatial and temporal evolution of the deformation and uplift of the Tanggula Range, and sedimentation of the Tuotuohe Basin, we conducted geologic mapping at a scale of 1:100,000 in the

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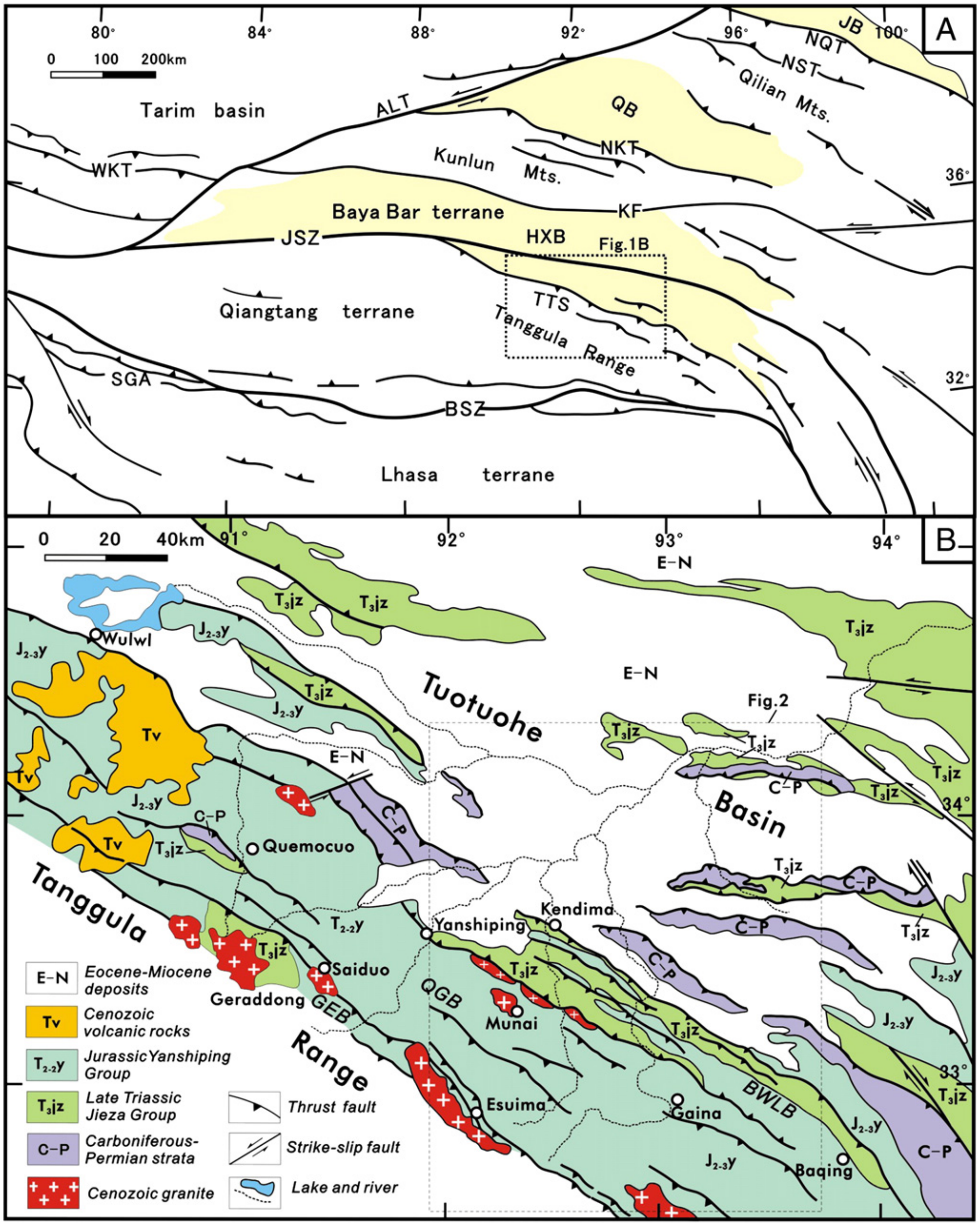

Fig. 1. A. Simplified tectonic map of the Tibetan Plateau showing major terranes, sutures zones, Cenozoic basins, and large thrusts discussed in the text. Major sutures: JSZ, Jinshajiang suture; BSZ, Banggongcuo-Nujiang suture; Major Cenozoic structures: ALT, Altyn Tagh fault; KF, Kunlun fault; TTS, Tanggula thrust system; WKT, Western Kunlun thrust belt; NKT, Northern Kunlun thrust belt; SGA, Shiquanhe–Gaize–Amdo thrust system; NST, Nanshan thrust belt; NQT, north Qilian thrust belt; Major Cenozoic basins: JB, Jiuquan Basin; QB, Qaidam Basin. B. Simplified tectonic map of the Tanggula Range and Tuotuohe region. Shown are main thrusts, strata, granites, and thrust belts of the TTS (GEB, Geraddong-Esuima thrust belt; QGB, Quemocuo-Gaina fold-thrust belt; BWLB, Baqing-Wulwl thrust belt).

Tanggula Range and the Tuotuohe region during 2002–2007. Our mapping results have revealed a previously unrecognized Tertiary thrust system and the Tuotuohe Foreland Basin (part of the Hoh Xil Basin). In this paper we present results of the deformation style of the Tanggula thrust system (TTS) and sedimentary fills of the Tuotuohe Basin, which provide robust constraints on the timing of the TTS, the sequential fill of the Tuotuohe Basin, and its relationship with the Tanggula Range uplift. These results also place constraints on the Cenozoic crustal shortening and uplift of the Tibetan Plateau.

2. Regional geological background

With an average elevation of 5800 m, and extending more than 350 km in a NW–SE direction, the Tanggula Range is the largest mountain belt in central Tibet. The Tuotuohe area and the middle part of the Tanggula Range lie along the northern edge of the Qiangtang terrane and continue across the Jinshajiang suture zone into the Baya Bar terrane (Fig. 1A).

The strata exposed in the study area are mainly Paleozoic to Cenozoic (Figs. 1B and 2). The Carboniferous Zaduo Group consists mainly of clastic and carbonate rocks of passive continental-margin shelf to basin facies, and the Permian Kaixinling Group is composed of clastic-igneous, and carbonate rocks, probably related to rifting.

The Late Triassic Jieza Group and the Jurassic Yanshiping Group are well exposed in the Qiangtang Basin (Li et al., 2002). The Jieza Group, consisting mainly of clastic and carbonate sediments, lies in the north of the Tuotuohe region and is unconformably overlain by the Jurassic and Tertiary rocks. The Yanshiping Group is more than 3300 m in thickness including the Middle Jurassic Quemocuo, Buqu and Xiali formations, and the Upper Jurassic Suowa and Xueshan formations. The Quemocuo, Xiali, and Xueshan formations consist mainly of clastic rocks, while the Buqu and Suowa formations comprise

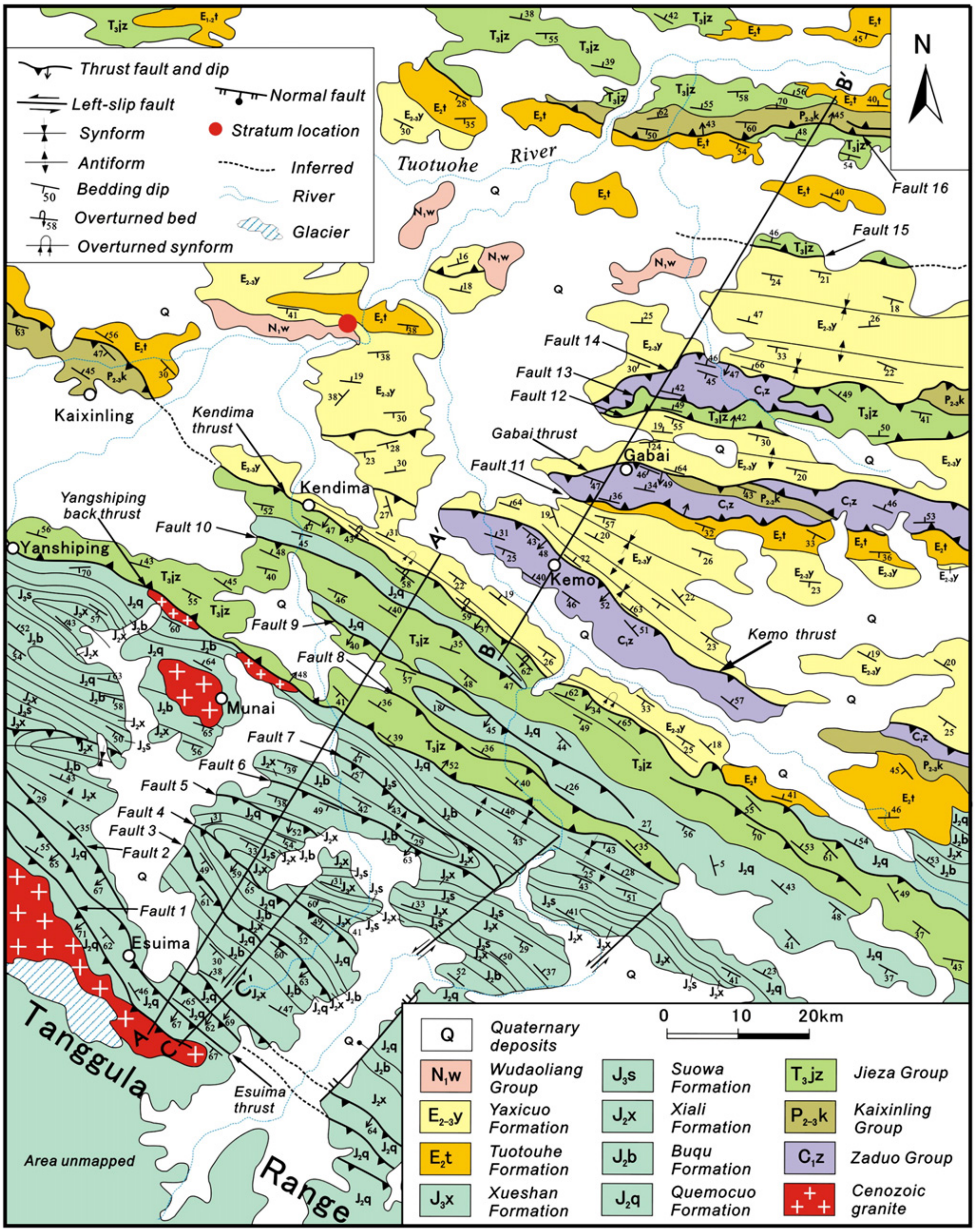

Fig. 2. Geologic map of the Tuotuohe-Esuima area (see Fig. 1B for regional location).

carbonate rocks. These formations were continuously deposited with conformable boundaries.

The Cenozoic strata consisting of terrigenous clastic and carbonate rocks are mainly exposed within the north of the research area in the Tuotuohe Basin (Fig. 1B). They are the Eocene Tuotuohe Formation, Eocene–Oligocene Yaxicuo Formation, and the Miocene Wudaoliang Formation. Among them, the Tuotuohe and Yaxicuo Formations are composed of conglomerate, sandstone, and siltstone. The sedimentation in the Tuotuohe Basin was continuous during the Eocene–Oligocene. The Wudaoliang Formation, which unconformably overlies the Yaxicuo Formation, consists mainly of lacustrine carbonate rocks. Magnetostratigraphic results indicate that the ages of the Tuotuohe, Yaxicuo and Wudaoliang Formations are 52.0–42.0 Ma, 42–23.8 Ma and 23–16 Ma, respectively (Yi et al., 2004; Liu et al., 2005; Wang et al., 2008). The Cenozoic strata and sedimentation provide an excellent record for study of the development of the Tuotuohe Basin and its relationship with the TTS.

The Cenozoic extrusive and intrusive igneous rocks are widely distributed in the study area and to different aerial extents (Fig. 1B). The volcanic rocks (45–22 Ma) consist mainly of shoshonitic to high-potassium calc-alkaline rocks, and originated from crustal shortening, thickening, and magma melting (Ding et al., 2000; Lai et al., 2001; Xia et al., 2010). The Cenozoic granites are distributed mostly along the peaks of the Tanggula Range (Fig. 1B), belong to syncollisional and post-orogenic crust-mantle types, and generated by the same mechanisms as the Cenozoic volcanism (Roger et al., 2000; Duan et al., 2005).

3. Deformation of the TTS

The TTS is parallel to the Tanggula Range and extends more than 320 km to the northwest, with width of 60–80 km (Fig. 1B). The tectonic style varies greatly in the TTS and can be divided into three belts based on the deformation and structural assemblage, including the Geraddong-Esuima thrust belt (GEB), the Quemocuo-Gaina fold-thrust belt (QGB), and the Baqing-Wulwl thrust belt (BWLB) (Fig. 1B). Here we present the deformation styles of the different belts as revealed by our research in the Tuotuohe-Esuima area (Fig. 2).

3.1. BWLB

The BWLB thrust belt is located in the Wulwl-Kendima-Baqing area in the northern TTS, and bounded on the north by the Tuotuohe Basin and on the south by the Yanshiping back-thrust fault (Fig. 2). The belt extends northwestward with a width of 20–30 km. Geomorphologically, it is the boundary between the medium–high mountain area and the northern low-mountain–hill area. The fieldwork revealed that this belt is characterized by thrust faults and imbricated slices. The deformed strata are mostly of the Jieza, Yanshiping, and Kaixinling groups and of the Tertiary from southwest to northeast. Within the BWLB, the thrusts are the Yanshiping back-thrust fault and the Kendima thrust associated with their subsidiary faults such as F8, F9, and F10 (Figs. 2, 3A).

The Kendima fault juxtaposes the Triassic strata over the Oligocene sediments in the Tuotuohe Basin (Fig. 4A, B). The fault planes dip mainly to the SW from 220° to 240° at angles of 34°–47°. Individual fault zones have widths varying from tens to hundreds of meters, and fault rocks have well developed breccia, cataclasite, and tectonic lenses (Fig. 4C), showing brittle–ductile characteristics. Fault slickensides, asymmetric tectonic lenses, small shear folds are seen (Fig. 4D and E), and tertiary stretching lineations in deformed conglomerate in the footwall indicate the thrust direction from southwest to northeast. According to statistics of the stretching lineations of the fault plane and the extensional lineations of the deformed conglomerate in the footwall in the Kendima area, the hanging wall moved mostly to the NE at dips of 40°–55° with a lesser lateral slip (Fig. 5a).

The hanging wall and footwall of the Kendima thrust are folded together, which can be attributed to a northeast-directed thrusting. The folds in the hanging wall are mainly asymmetric and overturned (Fig. 4F). The axes strike NW–WNW, the angles of dip are 35°–60°, and the plunge angles are 10°–20°. These folds appear tighter compared with the Tertiary folds in the Tuotuohe Basin (Fig. 5b and c). At the same time, the shape of these folds is disharmonic as a result of thrust-fault reconstruction. The Tertiary strata in the footwall of the thrust are overturned with the axial plane dipping SW (Figs. 2 and 4B), and an overturned anticline with a southward axial plane in the Triassic strata in the hanging wall indicates that the movement orientation was northeastward. Because the Tertiary deposits were distributed to the north of the Kendima thrust and the depocenter was developed in front of this thrust (see below), it is reasonable to conclude that the Kendima thrust was the southern boundary of the Tuotuohe Basin during the Eocene–Oligocene.

The Yanshiping back thrust is the main fault of the BWLB, and results the older Triassic Jieza Group over the Yanshiping Group with a maximum ~8 km of stratigraphic separation (Fig. 3A). This fault dips at angles of 48°–52° and the fault striations and asymmetric folds in the fault zone indicate a southwestward thrusting. The back thrust is the boundary of both the Triassic strata in the hanging wall and the Jurassic in the footwall. Moreover, the Cenozoic granites intruded

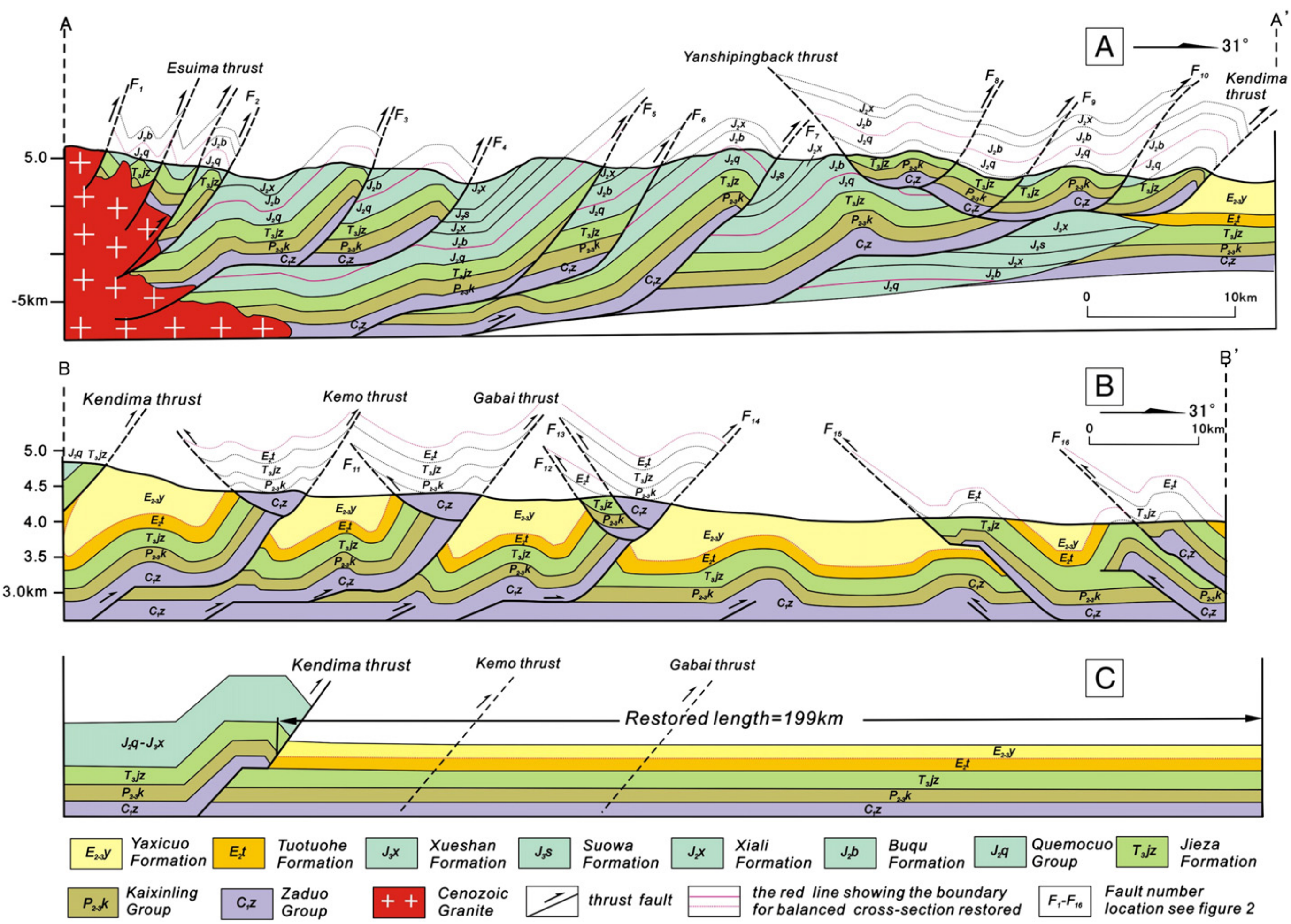

Fig. 3. Cross sections of the Tanggula thrust system (A) and Tuotuohe Basin (B), showing the deformation of TTS and syncontractional basin development associated with Paleocene–Oligocene shortening. Restored cross-section of A–A′ (C).

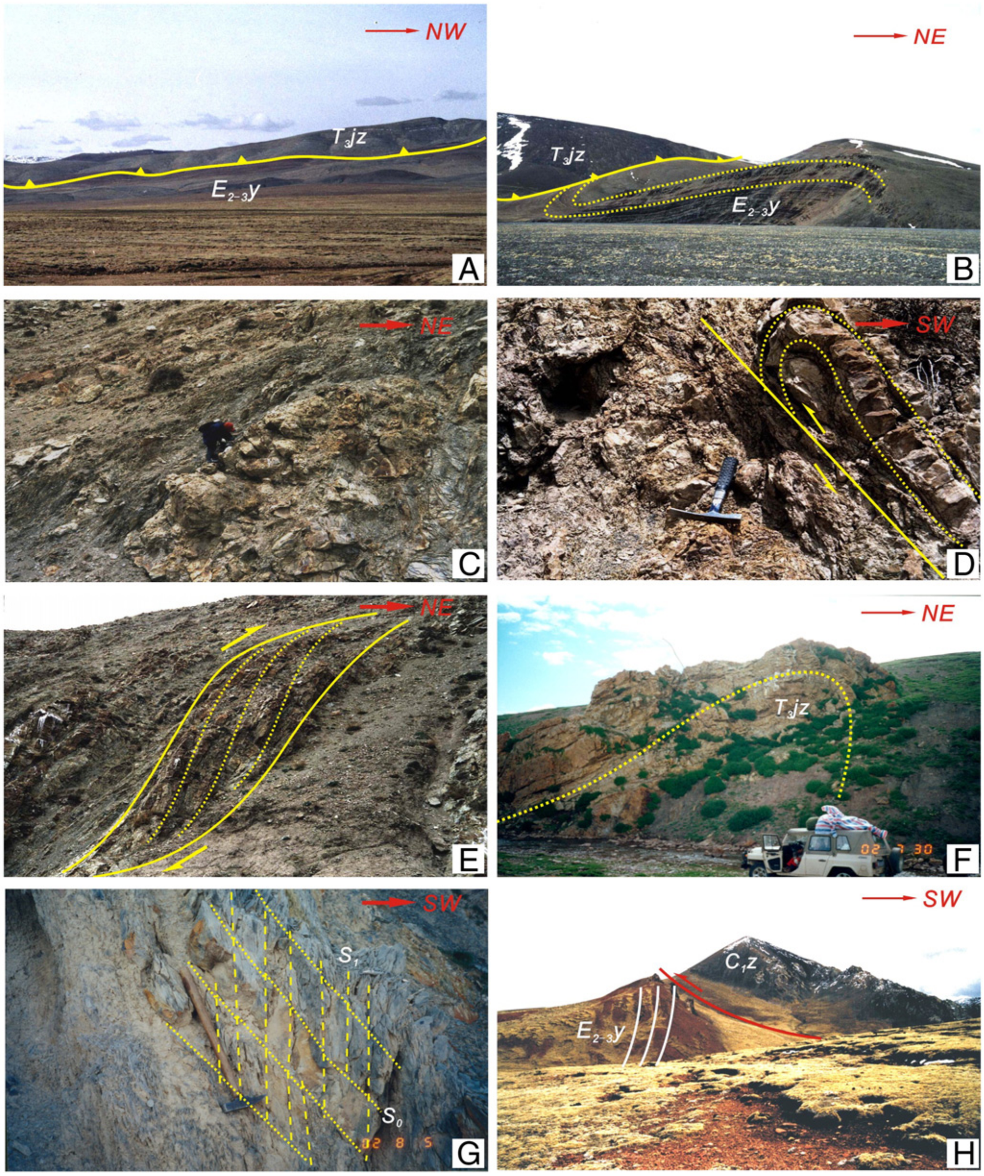

Fig. 4. Photographs of the Tanggula thrust system outcrops. (A) Kendima area, along Kendima thrust the Jieza Group thrusted upon the Tuotuohe Formation; (B) Kendima area, the Triassic Jieza Group thrust onto the Tuotuohe Formation, resulting in overturned syncline in the Tuotuohe Formation of the footwall; (C) Tectonic lens and cleavage of the Fault 8 east of Yanshiping; (D) Rootless shear fold in the Kendima thrust fault, showing the hanging-wall thrusted to NE; (E) Tectonic lens in Fault 9 east to Yanshiping, showing the hanging-wall thrusted to NE; (F) Kendima, overturned anticline in the Jieza Group in the hanging-wall; (G) the axial cleavages of the Quemocuo Formation in the Esuima area. S_0 and S_1 represent stratification and cleavage respectively. (H) Northern Kemo, along Kemo thrust, Carboniferous Zaduo Group thrusted upon the Tuotuohe Formation, the dipping angle of Tuotuohe Formation in the footwall is almost vertical.

along the back thrust suggest that the fault controlled the distribution of intrusions (Fig. 2).

3.2. QGB

The QGB belt is 30–40 km wide in the Munai area and 40–50 km wide in the Quemocuo region, respectively (Fig. 1B). The northern boundary of this belt is the Yanshiping back thrust, and the southern boundary is the Esuima thrust (fault 2) in the Esuima-Kendima area (Fig. 2). Deformed strata are represented mainly by the Upper Jurassic Yanshiping Group (Fig. 3A). Large-scale folds and thrust faults are common in this belt. Based on our statistical results to the south of Munai, the axes of folds extend northwest with dip angles of 35°–50° on various limbs (Fig. 5d). The synclines in southern Munai are large and open, whereas the anticlines are small and tight. The folds are disharmonic because they have been re-formed by the thrust, and consequently a set of subsidiary anticlines and synclines compose large compound synclines, such as the Yanshiping syncline (Fig. 2).

The thrusts are named F3–F7 with fault plane dip angles ranging from 43° to 63° (Fig. 5e), and with a fracture zone of 50–200 m wide. Cleavage, breccia, cataclasite, and fault clay are well developed within the belt. Moreover, deformed gypsum beds with different thicknesses were well developed in faults 4 and 6, and in other faults, implying that gypsum beds in the Yanshiping Group were probably secondary detachment layers.

The scale of folds is larger and the number of faults is fewer in the QGB compared with other belts, it can be inferred that the QGB is the weakly deformed unit in the whole thrust system.

3.3. GEB

This belt lies in the north of the main Tanggula Range (Fig. 1B) with width of about 8–15 km which consists of the Quemocuo and

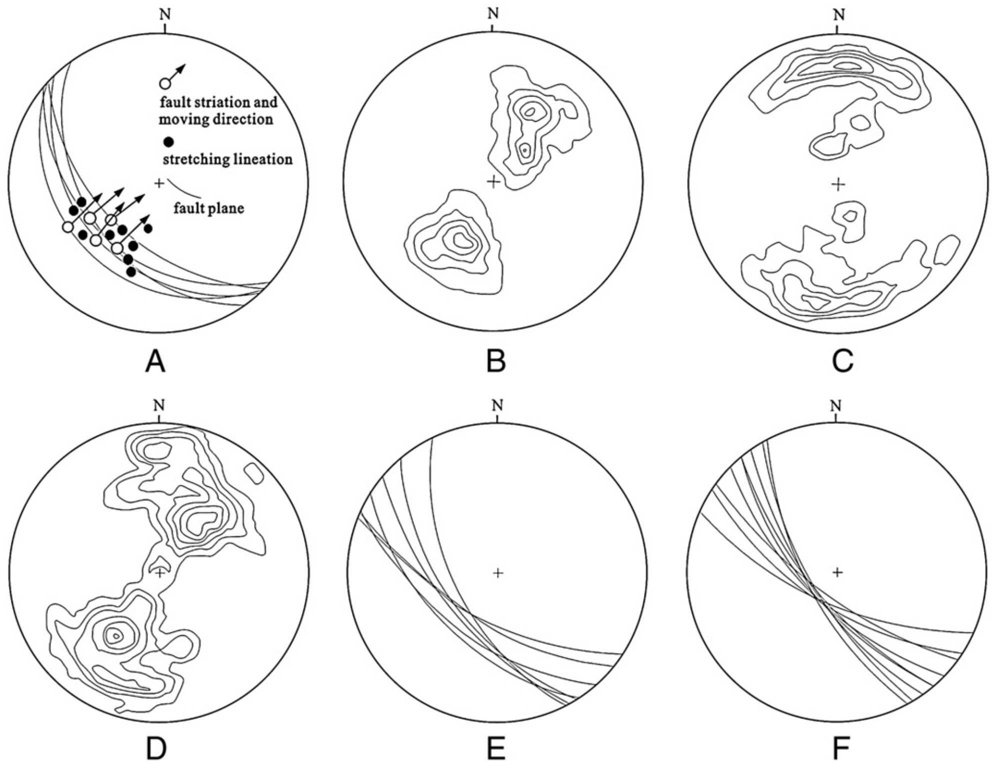

Fig. 5. Stereographic diagram of thrust fault and fold in the TTS and Tuotuohe Basin. Structural measurements are plotted on lower hemisphere equal-area stereonets. (A) fault plane and lineation stereographic diagram of the Kendima thrust; (B) π-diagram of the fold in the BWLB (n = 61, the contour values are 1.50–4.50–7.50–10.50–> 12%); (C) π-diagram of the Tertiary fold in Tuotuohe Basin (n = 57, the contour values are1.1–3.30–5.50–7.70–9.90–> 11.00%); (D) π-diagram of the fold in the QGB (n = 165, the contour values are 0.9–2.7–4.5–6.3–8.1–9.0%); (E) stereographic diagram of thrust fault in the QGB (n = 7); (F) stereographic diagram of thrust fault in the GEB (n = 10).

Jieza Groups as well as Cenozoic intrusive rocks. The strike of the thrust planes is NW 310°–330° with dip angles of 64°–71° (Figs. 5f and 6). The thrusts usually exhibit well developed cleavages, transportation foliations and tectonic lenses. Influenced by emplacement of granitic intrusions and thrust faulting, the fold shapes are difficult to discern. However, axial cleavages in the hinge region and the fold limbs are common (Fig. 4G), generally displaying an intensely deformed and high-angle imbricate thrust belt (Fig. 6).

4. Tuotuohe Basin

The Tuotuohe Basin covers an area of 13,000 km^2 at an average elevation of 4600 m (Fig. 1B). The basin is bounded in the south by the Tanggula thrust fault and the pre-Cenozoic strata in the north. It is one of the largest Cenozoic basins in the hinterland of Tibetan Plateau, and spans the northern part of the Qiangtang terrane and crosses the Jinshajiang suture zone (Fig. 1A). The pre-Cenozoic strata of the Tuotuohe Basin consist mainly of the Paleozoic, Triassic, and Jurassic sandstone and limestone (Zhang and Zheng, 1994). The Tertiary unconformably overlies the Late Triassic Jieza Group and the Jurassic Yanshiping Group in the northern basin (Fig. 2); however, the contact between the Tertiary and Mesozoic is faulted in the southern Tuotuohe Basin (Fig. 4H).

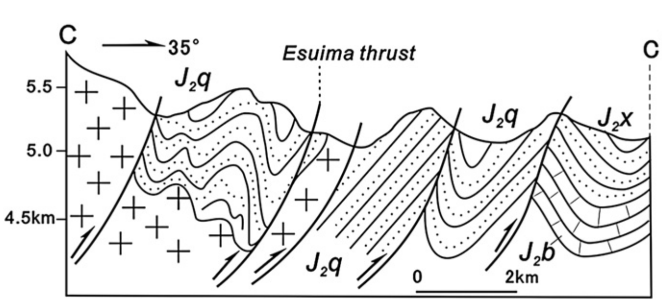

Fig. 6. Cross section of root thrust zone in the Esuima area, location and legend seeing Figs. 2 and 3.

4.1. Stratigraphy and sedimentary facies

The stratigraphic section of the Tuotuohe Basin is composed of the Eocene Tuotuohe Formation, the Eocene–Oligocene Yaxicuo Formation, and the Miocene Wudaoliang Formation, with a total thickness exceeding 3000 m. The rock association and sedimentary facies of each stratigraphic unit are best exposed in the Tongtianhe section (Fig. 7; see Fig. 2 for location).

The Tuotuohe Formation, with a thickness of 1216 m, is composed of medium-thick, variegated polymictic conglomerate, gravelly sandstone, and lithic sandstone. The gravel is mainly medium–coarse, subangular to subrounded, poorly sorted, and its component lithologies are complex, including violet-gray sandstone, fine sandstone, gray bioclastic limestone, and granite. The Fenghuoshan Formation to the south of the Kunlun Range is the equivalent (Liu and Wang, 2001; Liu et al., 2003). The measured section consists mainly of two sedimentary cycles that fined-upward (Fig. 7). Alluvial-fan and braided–meandering river facies alternate in the lower part of the formation. The fluviatile facies becomes dominant up section. Paleocurrents are directed mainly to the north (Fig. 7).

With a thickness of 1492 m, the Yaxicuo Formation mostly consists of red-violet, fine to coarse lithic sandstone, siltstone, mudstone, laminated micrite, fine conglomerate, and laminated marlstone in the lower part, and intra-calclithite and stratified limestone, and several layers of medium-laminated gypsum beds in the middle-upper part. The Yaxicuo Formation consists mainly of lacustrine deposits with rare fluvial sediment of different thicknesses in some parts. The lacustrine facies consists of shore, shallow-lake, and deep-lake subfacies,

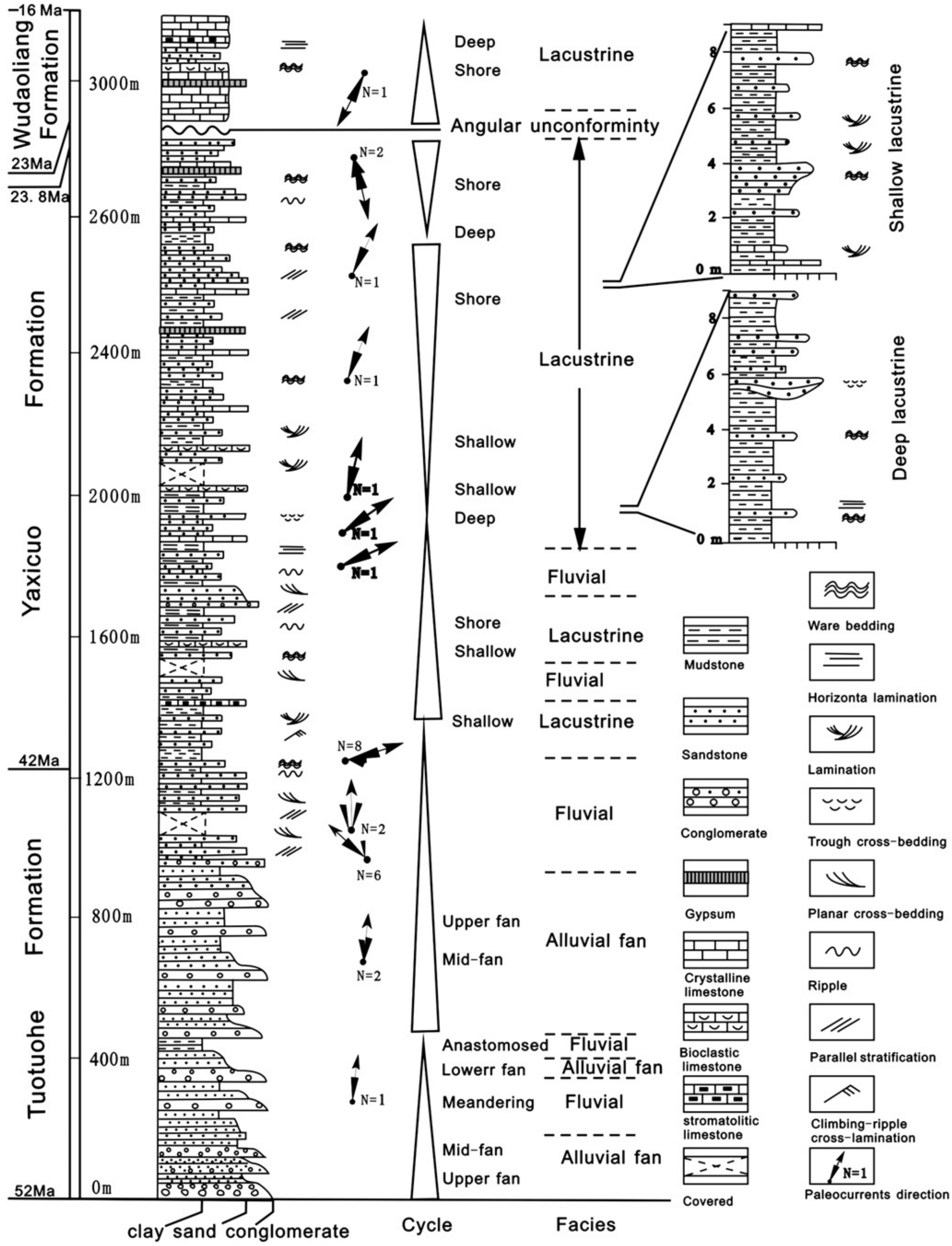

Fig. 7. Logs of the Tertiary strata in the Tuotuohe Basin. See Fig. 2 for location of measured section.

and three zones of cyclic sedimentation can be identified in this formation: the lower cycle deepens up section, and the middle and upper cycles shallow up section. Paleocurrents show northeast directions in the early stage and south directions in the late stage (Fig. 7).

The Wudaoliang Formation, with a thickness of less than 200 m overlies the Yaxicuo and Tuotuohe mudstone, and gray-black, thin to medium-thick laminated micrite formed in a deep lacustrine environment (Fig. 7).

4.2. Sequential filling of the Tuotuohe Basin

The Hoh Xil Basin can be divided into several sub-basins differentiated by sediment thickness of the stratigraphic sections, which are from south to north the Tuouohe sub-basin, Erdaogou sub-basin and the Wudaoliang sub-basin (Liu and Wang, 2001; Wang et al., 2002; Yi et al., 2004; Liu et al., 2005). Based on the measured sections, we constructed the sediment isopach maps of the Tuotuohe and the northern region (Fig. 8).

The isopach maps are based on a detailed study of sixteen outcrop stratigraphic sections and backstripping analysis of the surface stratigraphic data which include nine sections in the Tuotuohe Formation, seven in the Yaxicuo Formation, and over sixty-three paleocurrent directions in the Tuotuohe Basin (Fig. 8). The sections in the Erdaogou and the Wudaoliang sub-basin were modified from Wang et al. (2002) and Liu et al. (2001). The measured stratigraphic thickness was decompacted using the backstripping method after Van (1978) and Steckler and Watts (1978). Sedimentary isopachs were reconstructed by the interpolated point method based on the corrected stratigraphic thickness and the distribution of Cenozoic sediments. We assume that the distribution of present outcrops in the field represents the original depositional ranges.

During the deposition of the Tuotuohe Formation (Fig. 8A), two the depocenters of the Hoh Xil Basin were located in the Wulwl-Gabai and

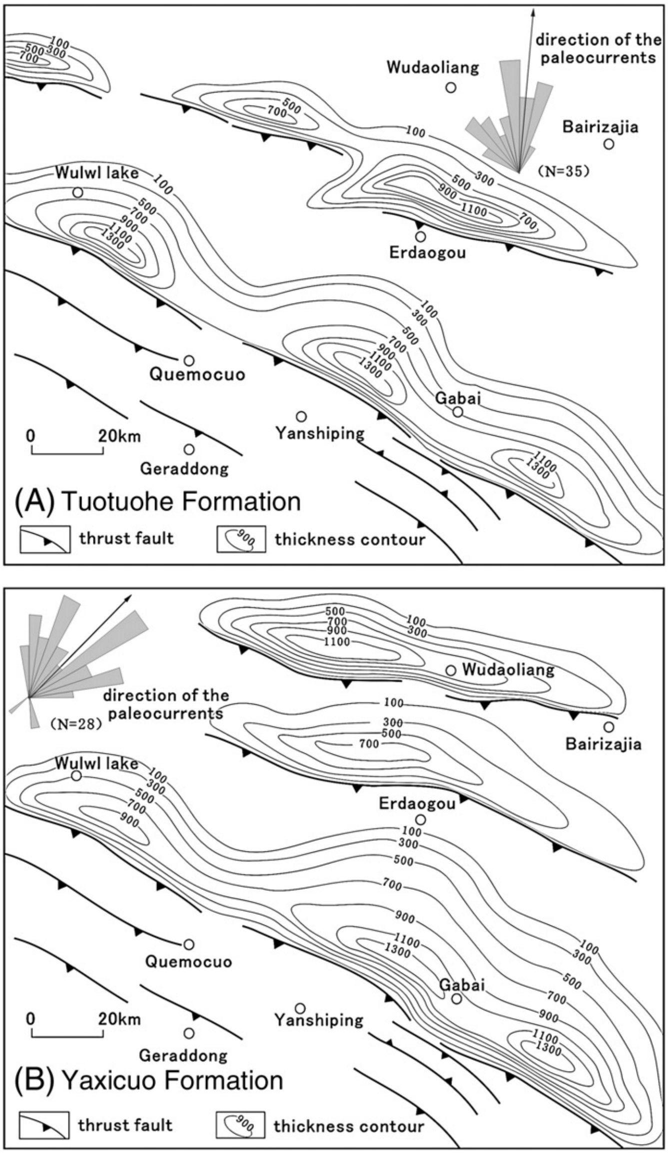

Fig. 8. Sedimentary rock isopach map (in meters) and paleocurrents of the Tuotuohe and Yaxicuo formations (rose plot for unidirectional strikes of paleocurrents, arrow shows mean direction, N = number of data).

Erdaogou areas. In the Tuotuohe area, the depocenter was limited to the Wulwl-Gabai area in the southern part of this sub-basin. The shape of the sub-basin is elongate, and the depocenter is in front of the TTS with a thickness greater than 1300 m. The paleocurrents (N = 35) flowed northward and northeastward (Fig. 8A). In the Erdaogou area, the thickness of the Tuotuohe Formation is less than in the Wulwl-Gabai area, and the paleocurrents were directed northeastward (Liu et al., 2001).

The Deposition of the Yaxicuo Formation was in three depocenters located in the Wulwl-Gabai, Wudaoliang, and Erdaogou areas (Fig. 8B). The paleocurrents (N = 28) in Wulwl-Gabai area were directed to the northeast, same as those of the Wudaoliang area (Wang et al., 2002). Changes in the paleocurrents and stratigraphic thickness indicate that sediments were derived from the southwest, and the depocenter migrated northeastward.

In summary, the sediments of the Eocene–Oligocene Tuotuohe Basins and other sub-basins were thicker in the south than in the north, indicating that the basin subsidence was greater in the south than in the north. This implies that the basin was asymmetrical, wedge-shaped, and southward-dipping. Numerous N–NE directed paleocurrents demonstrate that the source of the basin was from the Tanggula Range (Figs. 7, 8).

4.3. Deformation of the Tuotuohe Basin

Our field mapping indicates that the Eocene–Oligocene strata in the Tuotuohe Basin have undergone intense deformation. Deformed strata are mainly the Tuotuohe and Yaxicuo formations and pre-Cenozoic strata (Figs. 2, 3B). Folds and thrust faults are common in the basin, having formed in the fold-thrust association style. The axes of folds mainly are northwest-striking and parallel to the thrust faults. The dip angles of the limbs are ranging from 20° to 40° (Fig. 5c), and the anticlines and synclines are comparably developed. However, the strata on the footwall of the thrust fault are steep and overturned (Fig. 4B, H), indicating that the shapes of the folds were probably influenced by the thrust fault.

The tectonic profile shows that the movement orientations of the thrust faults were northeasterly-directed in the south section and southwesterly-directed in the north section (Fig. 3B). In the southern part of the basin the thrust planes dip to southwest, with angles of 47–52°. The hanging walls are composed mainly of Permian and Carboniferous strata. Back-thrust faults are well developed in the southern of the thrust system, such as the Gaibai and Kemo thrusts, which resulted in the Zaduo and Jieza Groups over thrust on the Eocene–Oligocene strata. Along the cross section (Fig. 3B), the thrusts in the northern part dip to northeast (F15 and F16) with angles of 40–45°, and the hanging walls are composed mainly of the Triassic strata.

5. Timing and crustal shortening of the Tuotuohe region

5.1. Timing of the TTS

The timing of the Tanggula thrust system can be constrained by the age of Cenozoic sediments and the angular unconformities of the basin as the Tuotuohe Basin was controlled by the TTS. The magnetostratigraphy of the Cenozoic strata indicated that the deposition of the Tuotuohe Formation in the Wulwl and Eedaogou areas began 52 Ma and 51 Ma respectively (Yi et al., 2004; Wang et al., 2008), which implies that the Tanggula thrust system started at least by the early Eocene.

The age of the Tuotuohe and Yaxicuo formation in the Tuotuohe Basin is of 52–31.3 Ma, 31.3–23.8 Ma, respectively (Yi et al., 2004; Liu et al., 2005; Wang et al., 2008). They are overlain by the undeformed Wudaoliang Formation. It was deposited during the interval of 23.0–16.0 Ma and outcrops well in most parts of the whole Hoh Xil Basin (Liu et al., 2001; Wang et al., 2002). The preceding research about deformation of the Tuotuohe Basin demonstrated that the Yaxicuo Formation is intensely folded and thrusted, whereas the Wudaoliang Formation in both the Tuotuohe Basin and the Erdaogou sub-basin is nearly horizontal. These observations imply that the termination time of the Tanggula thrust system was older than 23 Ma. Therefore, the TTS was active during 52–23 Ma.

5.2. Shortening estimates

Because of the lack of involvement of crystalline basement in our mapped areas, we hypothesize that the thrust system is of a thin-skinned type as shown in our cross section (Fig. 3). In order to restore the shortening of the TTS and the Tuotuohe Basin, the Jurassic and Tertiary strata are reconstructed separately on the basis of their deformation and thickness (Fig. 3). For estimating the shortening of the TTS, the boundary between the Middle Jurassic Buqu and Quemocuo formations is used as the marker bed, because they are characterized by carbonate and clastic rocks, respectively. Thus, this boundary is easily recognized and widely exposed in the section. To estimate the amount of shortening of the Tertiary strata, the boundary between the Tuotuohe and Yaxicuo formations is chosen as the marker bed, which is a set of thick conglomerate beds at the top of the Tuotuohe Formation composed mainly of carbonate rocks.

Two shortening ratios were estimated. (1) The Jurassic section is 59 km long now, whereas the original section was 148 km long, indicating that the shortening was 89 km, and the shortening ratio is 60%. (2) The Tertiary section in the Tuotuohe Basin is 103 km long now, whereas the original section was 199 km long, suggesting that the shortening is 96 km and the shortening ratio is 48%. Consequently, the shortening of the entire Tuotuohe area is 162 km with an average shortening ratio of 54%. Compared with the Jurassic shortening deformation, the early Tertiary section is the main intensely shortened section in the study area. The age of the TTS (52–23 Ma) and the undeformed Wudaoliang Formation (23–16 Ma) suggest that the main stage of crustal shortening was the Eocene–Oligocene in the Tuotuohe area. Our results for the Tertiary shortening in the Tuotuohe Basin are coincident with the conclusion by Wang et al. (2002) that the shortening ratio of the Fenghuoshan Basin is 43% since the late Oligocene, implying that the Tuotuohe area was intensely shortened before Miocene (23 Ma).

6. Discussion

6.1. Dynamics of the TTS

Our mapping indicates that the distribution of the TTS is consistent with the published Geologic Map of Tibet and Adjacent Region (Pan et al., 2004). In this map the TTS connects with the Jinshajiang suture at E88° and with the Lancangjiang fault at E95°, respectively, implying that the TTS extends for more than 600 km. Moreover, this thrust system may reach the Yushu–Nangqian area (Spurlin et al., 2005), suggesting the TTS in central Tibet is a regional large-scale thrust belt in the Tibetan Plateau (Fig. 1A).

The Cenozoic large-scale thrusts and crustal shortening in Tibet are commonly considered to be the result of the Indo-Asian collision and intracontinental deformation (Patriat and Achache, 1984; Achache et al., 1984; Harrison et al., 1992; Ratschbacher et al., 1994; Yin and Harrison, 2000). However, the initiation timing of the Indo-Asia collision is highly debated, ranging from the Late Cretaceous (Yin and Harrison, 2000) to the mid-Eocene (Rowley, 1998) or even the end of the Eocene (Aitchison and Davis, 2001). Some authors proposed a two-stage collision model including a soft collision stage between the margin of Great India and Asia (~65 Ma) and a hard collision stage (~45–40 Ma) (Lee and Lawver, 1995; Chung et al., 2005). As discussed above, the initiation timing of the TTS and the Tuotuohe Basin was about 52 Ma, which is coeval with timing of the Indo-Asian collision (Rowley, 1998) or initiation of the hard collision (Lee and Lawver, 1995; Chung et al., 2005). The cessation time of the thrust system is constrained to be about 23 Ma, which is contemporaneous with the Shiquanhe–Gaize-Amdo thrust system (Kapp et al., 2003), the Main Central thrust (Coleman and Hodges, 1995; Hodges et al., 1996), and the Gangdese thrust systems (Yin et al., 1994). The above observations suggest that the activity of the TTS was probably related to the Indo-Asia collision and subsequent shortening between the Eurasian and Indian plates.

6.2. Development of the Tuotuohe Basin and uplift of the Tanggula Range

The spatial and temporal relationship between faulting and sedimentation suggests the Tuotuohe Basin was a foreland basin controlled by the TTS. Moreover, the paleocurrent directions of the Tuotuohe and Yaxicuo Formations indicate that the basin was sourced from the southern region (Fig. 9A), suggesting that the Tanggula Range had been uplifted as the source of the Tuotuohe Basin during the Eocene–Oligocene.

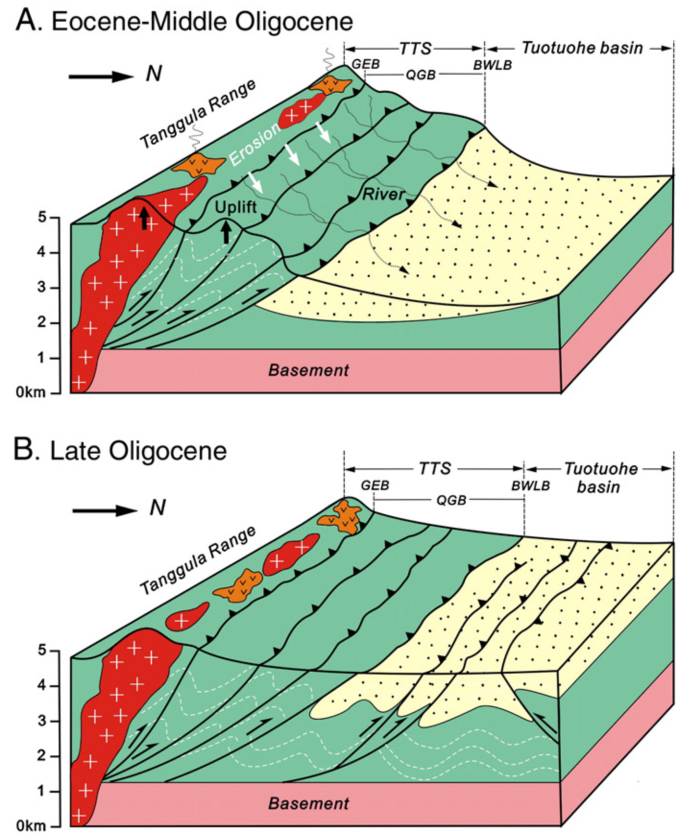

Fig. 9. Schematic model showing the uplift and basin evolution of the Tuotuohe region. Major thrust belts: TTS, Tanggula thrust system; GEB; the Geraddong-Esuima thrust belt; QGB, the Quemocuo-Gaina fold-thrust belt; and BWLB, the Wulwl-Baqing thrust belt.

Additionally, the thrusting of the TTS and uplift of the Tanggula Range should be episodic pulses according to the filling sequence, sedimentary facies, and the paleocurrent direction (Fig. 7). The Tuotuohe Formation is characterized by alluvial and fluvial sediments (52–42 Ma). The notable overcompensated deposition in the basin indicates that thrusting and uplifting were intense during this stage. The Tanggula Range was uplifted and then was eroded, providing the basin with sufficient sediments. The Yaxicuo Formation is dominated by lacustrine sediments with fluvial sediments. At this time the rate of deposition was reduced, and the directions of the paleocurrents were mainly northeast. The lacustrine sediments contain laminated intraclast and stromatolite limestone, indicating that the climate was warm and humid, and the thrusting activity was abated and relatively stable. In the middle to late Oligocene the lacustrine facies was still dominant. However, the cyclic sedimentation coarsened upward, and several sets of gypsum beds were formed toward the top (Fig. 7), indicating that the climate was becoming arid instead of warm and wet. Also the paleocurrent direction turned toward the south, showing that the paleogeomorphology had changed. In the late Oligocene, another intensive thrusting and uplift took place in the Tuotuohe Basin, resulting in the termination of the sedimentation and the angular unconformity between the Wudaoliang and Yaxicuo formations. Hereafter, lacustrine carbonate of the Miocene Wudaoliang Formation was reduced to a part of the sequence, while the clastic sediments became rare and thin, implying that the Tuotuohe Basin and the Tanggula Range had been penecontemporaneously uplifted and the source of the basin had diminished.

Cenozoic volcanism (45–22 Ma) in the study area was interpreted as the result of crustal shortening, thickening, and magma melting (Ding et al., 2000; Lai et al., 2001; Xia et al., 2010). Our study reveals that the crust was shortened more than 48% during the Eocene–

Oligocene. The synchronicity of the deformation and volcanism illustrates that the deformation resulted in crustal thickening, and that the melt of the thickened crust led to the large-scale magma intrusions and the high-potassium, calc-alkaline volcanism. Additionally, the quick cooling of the intrusions and sedimentary strata in the Tanggula Range during the Eocene–Oligocene (Roger et al., 2000; Duan et al., 2005; Wang, et al., 2008) further demonstrates that the Tanggula Range was intensely uplifted before the Miocene. Furthermore, gypsum layers are widely developed in the middle-upper part of the Yaxicuo Formation (Fig. 7), suggesting that the Tanggula Range was uplifted during middle-late Oligocene and led to the paleoclimatic change from wet to arid environment in the Tuotuohe Basin, which is consistent with the time of the desertification of Northern Tibet (Guo et al., 2002).

Studies of the Western Kunlun thrust belt, Northern Kunlun thrust belt, and North Qilian thrust belt north of the Tanggula Range suggest that the Cenozoic foreland basins were developed in the northern part of these thrust systems (Fig. 1A) (Tapponnier et al., 2001; Zhu et al., 2006; Yin et al., 2008). This demonstrates that the thrusts not only caused the uplift of the southern range but also uplifted the Tibetan Plateau, with sequential propagation from south to north (Tapponnier et al., 2001; Wang et al., 2002, 2003, 2004; Zhu et al., 2006). The Tanggula Range is the northern boundary of the Eocene–Oligocene plateau (Tapponnier et al., 2001; Wang et al., 2008). Because the TTS is the southernmost part of a large-scale thrust system thrusting to the north, the age of shoshonitic to high-potassium igneous rocks caused by intense crustal shortening becomes younger and younger northward (Wang et al., 2008), and the processes of crustal shortening and uplift show a north-moving trend, thus all these observations demonstrate that the Tanggula Range was uplifted during the Eocene–Oligocene (Fig. 9B), and so it may be considered as the northern boundary of the Eocene–Oligocene paleo-Tibetan Plateau.

7. Conclusions

Integrated geological investigations of the Tanggula Range-Tuotuohe region in the North Qiangtang terrane have provided a rich record of the Cenozoic deformation and basin development. Combined with the Cenozoic deformation, basin development, and magmatic activities, we drew the following conclusions. Influenced by the India-Eurasia collision in the Early Eocene, the Tanggula region was intensely deformation and led to crustal thickening and large-scale magmatic intrusion and extrusion. Under the control of tectonic and magma activities, the Tanggula Range was rapidly uplifted and eroded during the Eocene and Oligocene, and was the source area of the Tuotuohe Basin (Fig. 9A). In the late Oligocene, accompanied by regional shortening of the entire plateau, the Tanggula Range was again extensively uplifted (Fig. 9B), leading to the angular unconformity between the Oligocene and Miocene sediments. The fact that the Miocene strata are horizontal implies that the uplift resulting from thrusting was terminated, and that the whole area underwent a stage of denudation and planation. The development of large amounts of gypsum in the late Oligocene and the loess in the northern Tibetan Plateau show that the Tanggula Range had been probably uplifted to an altitude of 4000–5000 m and had become the northern boundary of the paleo-Tibetan Plateau in the Oligocene.

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