Mesozoic and Cenozoic deformations in the Raggyoraka area, Tibet: implications for the tectonic evolution of the North Qiangtang terrane

Xiao Liang1, Genhou Wang1*, Guo-Li Yuan1 & Xiaochao Che2

1 School of Earth Sciences and Resources, China University of Geosciences (Beijing), Beijing 100083, China
2 Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
*Correspondence: wgh@cugb.edu.cn

Abstract: The Mesozoic and Cenozoic deformations of the North Qiangtang terrane reflect a portion of the collisional tectonics of the Tethys Ocean, involving Late Triassic, Early Cretaceous and Cenozoic intraplate structures of shallow to superficial tectonic levels. The structural mapping of the Permian–Triassic structural layer indicates that the Mesozoic structural style is dominated by Early Cretaceous horizontal contractional deformations characterized by NW–SE-trending thrust faults and flexural-slip folds. These folds and thrusts were superimposed on Late Triassic buckle folds. Structural analysis of deformations of the Neogene and Quaternary sedimentary layers indicates that there was an obvious transition in the Cenozoic tectonic evolution of the North Qiangtang terrane, which can be divided into two deformation stages. In episode I (50–40 to 18 Ma), the crust experienced large-scale north–south horizontal shortening and vertical thickening shown by buckle folds and thrust faults. In episode II (18 Ma–present day), east–west passive extension formed conjugate strike-slip fault systems and pull-apart basins. During episode II, the Qiangtang basin was extruded eastwards, and a number of superficial north–south-trending buckle folds were formed.

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The lithosphere pattern of Eastern Asia, and especially the pattern of the Tibetan Plateau, was produced by the collision of fractured plates in northern Gondwana since Devonian time, and the suture zone of welding terranes records the evolution of the Tethys Ocean (Dewey et al. 1988; Yin & Harrison 2000; McCalfe 2006). The Longmu Co–Shuanghu suture, which is located in the central Qiangtang basin, is an extremely important Late Triassic tectonic zone in the Tibetan Plateau that separates the South Qiangtang accretionary complex belt and the North Qiangtang terrane; this suture retains important information regarding the evolution of the Paleo-Tethys Ocean (Li 1987; Li et al. 1995, 2009; Wang et al. 1996, 2009; Yin & Harrison 2000; Liu et al. 2002; Zhai et al. 2011; Liang et al. 2012). After the Triassic, the South Qiangtang accretionary complex belt and the North Qiangtang terrane merged into one unified terrane and became a Mesozoic–Cenozoic sedimentary basin (Wang et al. 2004; Liang et al. 2012). Around the year 2000, geological surveys were performed in the Qiangtang basin for the purpose of oil and gas exploration, and the overall tectonic framework of the Qiangtang basin was established (Huang 2001; Lei et al. 2001; Lu et al. 2001; Wang et al. 2001; Wang et al. 2004; Li et al. 2008). Since then, the North Qiangtang terrane has been an actively studied region of the Tibetan Plateau, especially regarding its Mesozoic and Cenozoic tectonic evolution. The major results of the tectonic research in this region may be summarized as follows: (1) geophysical data have been analysed and utilized to divide the Qiangtang basin into three tectonic units: the North Qiangtang depression, the central uplift belt, and the South Qiangtang depression (Huang 2001; Lu et al. 2001; Wang et al. 2001; Wang et al. 2004); (2) based on the type and degree of development of structures in various regions, the Qiangtang basin has been divided into a marginal thrust–fold belt, an internal composite fold belt, and a central basement metamorphic belt (Huang et al. 2001; Lei et al. 2001; Wang et al. 2001; Wang et al. 2004); (3) the combination patterns and distribution of folds and faults have been summarized and the stress field setting of these structures in the Qiangtang basin has been analysed (Huang 2001; Lei et al. 2001; Wang et al. 2004; Li et al. 2008). In addition, the Cenozoic deformation of the Qiangtang basin has attracted increasing attention from structural geologists, and studies concerning thrust faults, strike-slip fault systems and north–south-trending rifts have been continuously reported (Yin et al. 1999; Yin 2000; Yin & Harrison 2000; Li et al. 2001; Zhang et al. 2002; Taylor et al. 2003; Wang et al. 2008; Xie et al. 2010; Ratschbacher et al. 2011). Ratschbacher et al. (2011) reviewed the rifting and strike-slip shear in central Tibet and concluded that the currently active high-angel normal faults started c. 5 Ma ago, which were preceded by strike-slip faults and low-angle normal faults active at c. 18–7 Ma. The decade-long global positioning system (GPS) data have been used to explain the tectonics of the Qiangtang basin (Zhang et al. 2004; Gan et al. 2007), which showed a general sinistral shear strain and an eastward movement (Searle et al. 2011; Ratschbacher et al. 2011). Although general knowledge exists regarding the overall tectonic framework of the Qiangtang basin, existing studies of the tectonic evolution of the North Qiangtang terrane remain rather limited (Yin & Harrison 2000; Taylor et al. 2003; Wang et al. 2008; Ratschbacher et al. 2011; Searle et al. 2011). For example, the scales of these investigations, such as 1:100000 or 1:250000, are too small; thus, there is a lack of structural analyses on the outcrop scale. The deformation sequence of the North Qiangtang terrane since the Mesozoic has not been established, and folds and faults from different eras are often confused. Furthermore, there is a lack of systematic analyses of Cenozoic deformation in the North Qiangtang terrane, and there is a limited understanding of the combination of this deformation with the dynamic processes of uplift of the Tibetan Plateau (Taylor et al. 2003). The resolution of these questions would contribute to an understanding of collisional
tectonics of the Tethys Ocean and the Cenozoic tectonic uplift process in the central Tibetan Plateau.

To answer these questions, we conducted detailed structural mappings of the Raggyorcaka area in the central Qiangtang basin on both 1:50000 and 1:10000 scales; these results were then combined with high-precision remote sensing images to study the metre- to kilometre-scale structures within the Mesozoic and Cenozoic strata. Based on geometric and kinematic analyses on these structures, in this study we determine the stages of the Mesozoic–Cenozoic intraplate deformation processes in the North Qiangtang terrane and show the structural style and formation mechanisms at various deformation stages, thereby providing a detailed and accurate tectonic account of the geological evolution of the central Tibetan Plateau.

Regional geological setting

The Qiangtang basin is situated in northern Tibet, where it is sandwiched between the Jinsha and the Bangong–Nujiang suture zones (Fig. 1). With an area of nearly 180000 km², this basin is the largest Mesozoic–Cenozoic residual basin in China. The Qiangtang basin features extensive occurrence of Triassic–Jurassic marine sedimentary strata, and it was gradually transformed into a continental sedimentary basin after the Cretaceous (Zhao & Li 2000; Lu et al. 2001; Wang et al. 2001; Wang et al. 2004). Geophysical data indicate that the tectonic framework of the Qiangtang basin is dominated by an uplifted region sandwiched by two depressions. The central uplift of the basin in the Gangma Co–Gemu Ri–Mayer Kangri–Shuanghu area separates the North Qiangtang terrane from the accretionary complex belt with Gondwana affinity, which lies on the south side of the suture (Li et al. 1987, 1995, 2009; Liu et al. 2002; Wang et al. 2009; Geng et al. 2011; Zhai et al. 2011; Liang et al. 2012). The accretionary complex is primarily composed of Late Palaeozoic–Triassic terrigenous flysch and oceanic ophiolite (Wang et al. 2009), and the metamorphism–deformation process and geochemical characteristics of the rocks of this complex indicate that the Palaeo-Tethys Ocean demonstrated unidirectional northward subduction (Zhai et al. 2011; Liang et al. 2012). From the spatial perspective, the central uplift area and Late Triassic accretionary complex belt are consistent with respect to their morphology and distribution ranges (Fig. 1b). The North Qiangtang terrane on the north side of the suture zone was dominated by stable carbonate sediments in the Late Palaeozoic and Early Triassic, which were supplemented by a small quantity of continental or littoral–neritic clastic deposits (Li et al. 1995, 2009; Wang et al. 2001; Wang et al. 2004).
Deformations of the North Qiangtang 3

After the Triassic, the South Qiangtang accretionary complex was completely collaged onto the North Qiangtang terrane along the Longmu Co–Shuanghu suture to form one unified terrane. The Mayer Kangri Snow Mountain remained as an important palaeogeographical boundary and there is a significant difference between the deposition styles in the north and south of this unified terrane. The Jurassic deposition of the North Qiangtang terrane was characterized by intermingling between the land and the sea. Platform facies carbonate rocks are mixed with transitional facies clastic rocks, and an angular unconformity was constructed on them from the mid- to late Triassic (Wang et al. 2001; Wang et al. 2004). The deposition of the South Qiangtang basin is closely related to the evolution of the Bangong–Nujiang Ocean of Meso-Tethys. The depositional environment changed gradually from neritic facies to bathyal–abyssal facies, and later changed to transitional facies in the Late Triassic to Middle Jurassic (Wang et al. 2001, 2004). In the Cretaceous, the sedimentation in the Qiangtang basin was largely transformed to continental facies and was subjected to overall uplift and denudation in combination with a minor distribution of clastic deposits of fluvial–lacustrine facies (Wang et al. 2001, 2004). Since the Cenozoic, as a result of the collision between the Indian and Eurasian plates, the Qiangtang basin has been constantly uplifted, and its sedimentation has been characterized by clastic deposits of fluvial–lacustrine facies (Wang et al. 2001, 2004).

The deformation of the North Qiangtang terrane since the Mesozoic has been closely related to the collisional tectonics resulting from the closures of the Tethys Oceans (Metcalfe 2006) and is superimposed by the tectonic responses to Late Triassic orogenesis of the Palaeo-Tethys Ocean, Early Cretaceous orogenesis of the Meso-Tethys Ocean, and Cenozoic orogenesis of the Neo-Tethys Ocean respectively. There are relatively complete North Qiangtang strata in the Raggyorcaka area (Figs 1 and 2), which can be divided into the following three structural layers based on angular unconformity surfaces: (1) Upper Permian–Middle Triassic; (2) Miocene–Pliocene; (3) Pleistocene. The various structural layers exhibit the deformation of the North Qiangtang terrane that occurred in different periods; although their structural styles are distinct, all of these layers demonstrate shallow to superficial intra-plate buckle folds, and brittle faults, with the phenomena of structural superimposition.

### Structural style of the Upper Permian–Middle Triassic rocks

The exposed bedrock in the Raggyorcaka area is in good condition; therefore, we utilized true-colour remote sensing images (three-, two-, and single-band images with 30 m resolution) from the Landsat-7 satellite and true-colour images (with 2.5 m resolution) from Google Earth to interpret the tectonics of certain folds and faults and to extract relevant geometric and kinematic parameters.

<table>
<thead>
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<th>Deformation stage</th>
<th>Time</th>
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<th>Trend of fold axis</th>
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<td>D3</td>
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**Table 1. Deformation sequence of the P–T strata in Raggyorcaka area**

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</tr>
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**Fig. 2.** The structural style of Late Permian–Middle Triassic sedimentary strata in the Raggyorcaka area of North Qiangtang terrane. In the stratigraphic legend, the strata become younger from the bottom to the top. The thrust fault belt is composed of six faults: F1, F2, F3, F4, F5, and F6. The cross-section A–A’ indicates that F4 and F5 have step and ramp geometries, and exhibit an imbricated combination.
structural style, which is manifested as thrust faults, buckle folds and a fold-accommodation fault (Fig. 2).

Three-stage superimposed fold

The south bank of the Raggyorcaka area developed an extremely large superimposed fold of c. 3 km in width, which was formed by the superimposition of buckle folds at three stages (B₁, B₂, B₃); the overall profile of this fold is dominated by the second-stage closed syncline (B₂) (Figs 2 and 3). The third-stage folding (B₃) caused the limb of the syncline to bend into c. 5 km wide gentle waves, and the purplish red conglomerate flag layer forms a gentle fold with 1.5 identified full wavelengths, and an interlimb angle of 140–150°. This upright plunging parallel fold has a hinge that gently dips towards SW 195–200° (Fig. 3).

The second-stage syncline (B₂) is a flexural-slip fold with an interlimb angle of 20–40° and a >2 km wide hinge zone (Fig. 3). This syncline appears as a thick-top fold, and the curvature is much greater for the external fold strata than for the inner fold strata. The thickness at the core of the fold is substantial, and the outcrop that is sandwiched between the top of the Kanglu Formation and the purplish red conglomerate interlayer has a horizontal thickness of 308 m in its NE limb, 2126 m in its hinge and 446 m in its SW limb; the thickening ratio is 4.7–6.9 (Fig. 3a). This fold appears as an upright plunging fold with a hinge dipping towards the ESE, and the subsidiary folds also show a coincident hinge attitude (inset in Fig. 3a). The occurrence of strata is reversed in the hinge of the syncline, with the Kanglu Formation overlain on the Yingshuiquan Formation (Fig. 3a and b). The reconstruction of the folding features reveals that the second-stage syncline was superimposed on the prior NE–SW-trending syncline (B₁) and that the core strata were still the Yingshuiquan Formation, with the Kanglu Formation and Raggyorcaka Formation recurring symmetrically on both sides of the hinge (Fig. 3c).

Fold-accommodation fault

As shown in Figure 2, thrust fault F₁ is distributed along the NE limb of a giant B₂ syncline, extending in a nearly east–west direction with an outcrop length of c. 4.5 km. F₁ obliquely cuts across the Raggyorcaka, Kanglu and Yingshuiquan Formations on the NE limb of the syncline, and the thickness of the Kanglu Formation changes suddenly along the trend of the fault (Figs 2 and 3). F₁ is an out-of-syncline thrust fault and extends from the core towards the exterior of the NE limb of the syncline (Fig. 3). The geometric and kinematic features of this fault indicate that the thickness of the fold core rapidly increases to cause a volume imbalance, which eventually led to the formation of a fold-accommodation fault that adjusted the increasing strain. The north wall of the F₁ fault remained stable, whereas the south wall of this fault slid eastward and was laterally extruded from the syncline core. The apparent offset in map view indicated by the top of the Kanglu Formation is 2662 m, whereas the lower purplish red conglomerate interlayer shows a far smaller distance

Fig. 3. The characteristics of three-phase superimposed folds and thrust faults (F₁, F₂, F₃ and F₄). The dashed line represents the purplish red conglomerate flag layer. (a) The giant syncline (Map data: Cnes/Spot image from Google, Mapabc.com), attaching the stereographic projection of the secondary fold hinge in Schmidt net (lower hemisphere). (b) A detailed schematic diagram of the superimposed folds: from old to new, the three stages of buckle folds are represented by B₁, B₂ and B₃. (c) A diagram of the reconstructed B₂ fold profile, indicating that the B₂ syncline is superimposed on the B₁ syncline, which has its axis oriented NE–SW. (d) The geometry of the thrust F₄ (Map data: Cnes/Spot image from Google, Mapabc.com). (e) A simplified cross-section for F₄.
of 304 m (Fig. 3a). This enormous difference indicates that this fault was first formed in the hinge zone and then gradually developed toward the limbs after cutting through the rock strata. Thus, the earlier fractured layer would exhibit the maximum final displacement.

Google Earth true-colour images indicate that the F1 fault cuts through the WNW–ESE-trending second-stage syncline (Bj) and then is truncated by thrust fault F2 (Fig. 3a), which indicates that the detailed process of the second-stage contractional deformation occurred in the following manner. First, the rock strata underwent continuous ductile deformation to form curved folds. Subsequently, a fold-accommodation fault occurred to adjust the volume imbalance in the cores of these strata, and eventually ruptures occurred to form thrusts because the continuous bending of rock strata could not adjust to the increasing strain.

**Thrust fault belt**

The thrust belt is located to the south of Lake Raggyorcaka, and is composed of five thrust faults (Fig. 2); from north to south, these are labelled F2, F3, F4, F5 and F6. The faults commonly possess flat-ramp features, and the hanging walls generally form anticline-or syncline-type fault-bend folds as a result of the stepped fault plane. The footwalls were cut by thrust faults or the hanging walls and the thickness of specific layers exhibits significant thinning or thickening in certain local regions.

These thrust faults all appear in the form of footwall ramps in outcrop and extend in a NW–SE direction on the horizontal plane. In particular, the thrust directions of F2, F4, F5 and F6 are all towards the NW or NE. The detailed characteristics of the three major thrust faults are as follows.

1. **Thrust fault F2**
   - F2 extends in a NW–SE direction with a length of c. 1.6 km in map view, and its NW end cuts and offsets the fold-accommodation fault F1 (Figs 2 and 3). In outcrop, F2 exists as a footwall ramp that cuts the SW-dipping monoclinal carbonate layers in the footwall on the north side, and the thrusting layers of the hanging wall have developed an anticlinic fault-bend fold with its NE limb truncated by the ramp (Fig. 4a). This anticline appears as a parallel fold with a hinge zone of c. 30 m width and an interlimb angle of c. 130°. It also occurs as an inclined horizontal fold with an axial plane dipping to the NE at a moderate angle but a nearly horizontal hinge.
   - Thrust fault F2 developed a cleavage belt with a width >10 m and has a continuous slaty cleavage with planes of c. 1 cm width; these cleavage planes are densely arranged in parallel and demonstrate an extremely steady occurrence. Micrite in the belt underwent substantial metamorphism and changed to fine-grained brown and purple marbles by recrystallization.

2. **Thrust fault F4**
   - F4 is located in the central part of the thrust fault belt and extends in a NW–SE direction for c. 4 km (Figs 2 and 3d). It is also a footwall ramp that cuts the giant SE-plunging tight anticline on the NE side, and the siltstone layers of P4r are clearly truncated and gradually disappear to the NW (Fig. 3d). The hanging-wall rock strata form a SE-plunging syncline that is truncated by the thrust ramp (Fig. 3d and e). This syncline displays an overturned strata sequence in which the lithic sandstone layers of T1k in the core overlie the limestone layers of T1g, indicating that this fold formed as a result of a step on the thrust fault plane but is not a subsidiary fold of the giant anticline.

3. **Thrust fault F5**
   - F5 is located in the southern part of the thrust fault belt and extends in a NW–SE direction for c. 5 km (Figs 2 and 4c). In outcrop, F5 exists as a footwall ramp, with clear truncation geometry in which the hanging-wall carbonate layers on the SW side of the fault intersect the footwall layers on the other side (Fig. 4b). The northern and central segments of F5 cut the lithic sandstone that is sandwiched in the limestone layers of T1g in the footwall, and the outcrop widths of the rock strata are highly discontinuous in a NW–SE direction. The thickness of the sandstone layer rapidly increases in the northern segment of the fault, and the outcrop width reaches 510 m, whereas thinning occurs in the middle segment, and the outcrop width is typically 123–339 m (Fig. 4c). The SE end of F5 developed a fracture zone of 3–25 m in width, which developed a group of prominent and extremely large purplish red lens bodies that extend NW–SE. These lens bodies were between 1 × 3 and 15 × 40 m in size, and the long axes of these bodies were highly consistently aligned with the trend of the fault zone. The limestone in the lens bodies generally underwent metamorphism and recrystallization to become microcrystalline or fine-grained marbles, which were subsequently ruptured to form breccias with fissures filled by purplish red limonite veinlets.

   The surfaces of these marble lens bodies are very smooth and flat slickensides. These lens surfaces are associated with banded striae and grooves with parallel alignment; the deep to shallow direction of these grooves indicates that the hanging wall (the SW wall) moved in a NE direction.

4. **Thrust fault F6**
   - F6 is located at the south end of the thrust fault belt, on the SW side of F5, and extends in a NW–SE direction, with an outcrop length of c. 5 km (Figs 2 and 4c). The hanging wall of the southern segment of thrust F6 developed a fault-bend fold occurring as a parallel upright-plunging syncline, with a hinge zone width of c. 30 m and an interlimb angle of c. 100°, and a hinge occurrence of 140°–241°. In outcrop, F6 is a footwall ramp, and the limestone layers near the fault zone underwent obvious recrystallization and became marbles. True-colour images from Google Earth indicate that the fault cuts through monoclinal rock strata extending in a NW–SE direction in the footwall and that the hanging-wall syncline structure clearly truncates the ammonite-bearing sandstone and micrite layers (Fig. 4c and d).

   This syncline is subsequently superimposed by upright plunging folds with an axis direction of approximately NE 30°, and its limb carbonate layers form a full fold wavelength of 60 m, with an interlimb angle of 120–130°. The syncline hinge underwent undulation in a NW–SE direction, and in the middle segment of thrust fault F6, the syncline hinge has shifted to plunge NW.

**Cenozoic deformation**

Owing to the influence of the Cenozoic tectonic uplift of the Tibetan Plateau, the Qiangtang basin was widely filled with fluvial–lacustrine sediments. The Cenozoic strata in the Raggyorcaka area can be broadly divided into two structural layers: the purplish red Miocene–Early Pliocene fluvial–lacustrine clastic rocks named the Kangtog Formation and the Pleistocene alluvial and fluvial sediments. In outcrop, the deformations of these two structural layers all appear as buckle folds and brittle faults at a superficial level; however, their differences in structural types and combinations record important clues about the uplift of the Qiangtang basin.

**Miocene–Early Pliocene deformation**

Around Lake Raggyorcaka, the folds and faults in the sedimentary layers of the Kangtog Formation can be divided into two stages. The first-stage folds involve NW–SE-trending synclines with wide interlimb angles and large hinge zones of 3.5–6 km width. Stereographic projection of the Sb bedding in a Wulff net indicates that the axes of folds at this stage extend primarily in a NW–SE direction.
contractional deformation in a nearly north–south direction in the Cenozoic. Evidence for the second-stage deformation is provided by anticlines, synclines and fold-accommodation faults that extend in a nearly north–south direction. These parallel folds generally occur as upright horizontal folds with an axis direction range of 5–13°, an interlimb angle range that is generally 130–150°, and a hinge zone width range of 20–50 m. The limbs of the folds, particularly near the inflection points of the folds, often form small-scale thrust faults (Fig. 5). The geometric and kinematic features indicate that these faults are fold-accommodation faults that have been described as wedge thrusts in the syncline limbs with ramp-like morphologies (Mitra 2002). The rock strata in the hanging walls are nearly parallel to the fault planes and intersect the footwall layers.

At 50 km to the south of Lake Raggyorcaka, purple–red lake facies clastic and carbonate layers of the Kangtog Formation clearly show superimposed three stages of contractional deformation, D1, D2, and D3 (Table 2). Pale arkose layers sandwiched between purple–red layers form a c. 500 m wide circular structure that resulted from three phases of folding deformation in a nearly perpendicular direction (Fig. 6a). The D1 deformation buckled the thick-bedded siltstone and carbonate layers into isoclinal or tight recumbent folds, indicating a relatively large contractional strain (Fig. 6b). East–west-trending thrust faults and nappé structures also occur with these folds, and isolated Permian limestone klippen usually overlie the Kangtog Formation purple–red siltstone layers in outcrop. The D2 deformation caused buckling of the D1 isoclinal folds into north–south-trending open buckle folds (Fig. 6c). Anticlines in outcrop often occur as upright plunging folds, but their hinges dip to north or south alternatively as a result of the D3 north–south-trending contractional deformation (Fig. 6a). Buckle folds of D2 and D3 are generally parallel anticlines or synclines (Fig. 6c and d), which imply much smaller strain than for D1.

Pleistocene deformation

The concave bank on the western side of the Bu Zang Ai River in the southern part of the Raggyorcaka area developed a first terrace with a height of c. 20 m (Fig. 7a). Li et al. (2006) obtained a sedimentary age of 86.9 ka using the uranium-series technique for this alluvium. The west-dipping East Yibug Caka normal fault, which merges with the NNE–SSW-striking Bu Zang Ai left-slip fault to the north (Taylor et al. 2003), produced an east–west-trending extensional stress field in this location. Small-scale (0.5–1 m in profile) synsedimentary conjugate normal faults (Fig. 7c) with minor displacements of 5–10 cm intersect prior buckle folds. These open parallel folds of 0.15–7 m width are generally upright horizontal or inclined horizontal types with NW–SE-extending axes (Fig. 7a and b) indicating contractional deformation in a NE–SW direction.

Discussion

Timing of the thrust faults

For the thrust fault belt to the south of Lake Raggyorcaka, the strata that are involved in deformation are of Late Permian–Middle
Triassic age, and it is possible to establish that these faults were formed after the Middle Triassic. According to the interpretation of geological maps of earlier researchers using Google Earth and Landsat-7 true-colour remote sensing images, the Middle Jurassic continental clastic deposits on the north bank of Lake Raggyorcaka also underwent deformations similar to the above-mentioned thrust faults and the Lower Triassic Kanglu Formation thrusts onto the Jurassic clastic deposits. This phenomena would account for the absence of strata of Early Triassic–Early Jurassic age, which indicates that the formation era for the thrust faults is after the Middle Jurassic. Furthermore, Miocene–early Pliocene continental clastic rocks in the Raggyorcaka area overlie the P2–T1 strata and the thrust fault belt after an angular unconformity without being involved in the thrusting deformation. Therefore, we can determine that the second-stage thrust faults and buckle folds (B2) occurred in the Early Cretaceous; these deformations might have been caused by continental collision related to the Late Jurassic–Early Cretaceous closure of the Bangong Lake–Nujiang Ocean on the south side of the Qiangtang basin (Yin & Harrison 2000; Geng et al. 2011). In addition, the first-stage NE–SW trending buckle fold (B1) most probably reflects contractional deformation caused by the Late Triassic closure of the Palaeo-Tethys Ocean (Li 1987; Wang et al. 2009; Liang et al. 2012).

### Timing and formation mechanism of north–south-trending buckle folds

Buckle folds that are oriented in a nearly north–south direction are distributed across the North Qiangtang terrane; based on this trait, previous studies have speculated that there once existed a Cenozoic east–west-oriented stress field (Wang et al. 2004; Yong 2004; Li et al. 2005; Jia et al. 2006). However, there is controversy on the era during which these folds were formed, which has been given as the end of the Cretaceous (Jia et al. 2006), 30–20 Ma (Yong 2004), the Middle Himalayan (Li et al. 2005) or the Late Himalayan (Wang et al. 2004).

These folds with axes in a nearly north–south direction are also well developed in the Raggyorcaka area. They are distributed in the Early Cretaceous thrust fault zone, Miocene–early Pliocene Kangtong Formation, and Late Triassic accretionary complex around Mayer Kangri. In the accretionary complex, these folds generally occur as large-scale antiform and synform structures and feature broad hinge zone widths of 20–1300 m and interlimb angles of 110–120° (Fig. 1a). These parallel folds occur as an upright horizontal type with a hinge extending mainly in the NE 0–15° direction. In the thrust fault belt to the south of Lake Raggyorcaka, the hanging-wall syncline of thrust fault P1 is superimposed by an upright plunging anticline with a NE 30° axis (Fig. 4d), and the purplish red conglomerate of the Kanglu Formation on the north side of P3 is superimposed by an upright plunging fold with a NE 195–200° axis (Fig. 3). The purplish red continental clastic layers of the Kangtong Formation formed these buckle folds with hinges extending in a 5–15° direction (Fig. 5).

Because the north–south-trending buckle folds were not developed in the Pleistocene sediments of the Raggyorcaka area, the present study establishes that these folds were formed during the Pliocene. Regionally, instead of occurring in isolated or local outcrops, these folds are widely distributed in the central and northern parts of the Qiangtang basin. This indicates that north–south horizontal contractual deformation undoubtedly occurred in the Qiangtang basin during the Pliocene.

Since 50–40 Ma, the Indian plate was in full contact with the Eurasian plate, and the Tibetan Plateau therefore entered the post-collision phase (Yin & Harrison 2000; Mo et al. 2007; Searle et al. 2011). Horizontal north–south-directed contractual deformation became active during this phase. The Mesozoic–Cenozoic intraplate deformation of the Qiangtang basin was constrained by the tectonic conditions of compression in a north–south direction, and the axial directions of the buckle folds were therefore largely aligned east–west (Huang 2001; Lei et al. 2001; Li et al. 2008). The existence of north–south-trending buckle folds appears to conflict with the tectonic setting, but the possibility that the internal stress field was reversed in the Qiangtang basin cannot be discounted. Tapponnier & Molnar (1976) and Peltzer & Tapponnier (1988) suggested that under the constraints of extremely large strike-slip fault systems, the internal terrane of the Tibetan Plateau underwent substantial eastward extrusion. The Karakoram and Jiali right lateral strike-slip fault belts drove the eastward motion of the Qiangtang terrane during this time (Armijo et al. 1986). Although the displacement and slip rate of the main strike-slip faults are limited (Taylor et al. 2003; Searle et al. 2011), numerous strike-slip faults or conjugate strike-slip fault systems that developed inside the plateau could each contribute to the overall slip; thus, the lateral extrusion of the plateau may be decomposable into the eastward extrusion of a series of small terranes (Yin 2000; Taylor et al. 2003). The extrusion of the Qiangtang basin is...
strongly supported by present-day GPS measurements (Zhang et al. 2004; Gan et al. 2007). Therefore, we speculate that these types of folds are most probably related to the extrusion structure of the Tibetan Plateau and represent a derivative deformation of strike-slip fault systems. We assume that the lateral eastward extrusion of the Qiangtang basin dragged the shallow crust eastward or northeastward, causing the rock strata to undergo slight contractional deformations that are represented by north–south-trending buckle folds.

The division of Cenozoic tectonic stages

The Cenozoic intraplate deformations in the Qiangtang basin undoubtedly reflect a remote tectonic response to the collision
Episode I is characterized by consistent with the post-collision stage between the Indian and Eurasian plates. The deformation of structural layers in the Raggyorcaka area indicates that there was a distinct transition which could divide the Cenozoic deformation of the North Qiangtang terrane into two stages of episode I and episode II (Table 3).

Episode I is characterized by north–south horizontal contraction. Buckle folds and thrust faults were developed in a nearly east–west direction in the North Qiangtang terrane (Table 3). This episode should be consistent with the post-collision stage between the Indian and Eurasian plates after 50–40 Ma causing the Tibetan crust to undergo large-scale shortening (Yin & Harrison 2000; Mo et al. 2002). Yin & Harrison (2000) found that there are three important Tertiary thrust fault systems distributed in central and Northern Tibet including Qiangtang basin. The Miocene–Pliocene Kangtog Formation around the Raggyorcaka area formed isoclinal similar to the crustal extension with \( \sigma_1 \) subvertical. These studies reveal that \( \sigma_1 \) became subvertical due to the thickened crust, which may easily make conjugate strike-slip fault systems develop within the central Plateau.

Yin & Harrison (2000) found that there are three important Tertiary thrust fault systems distributed in central and Northern Tibet including Qiangtang basin. The Miocene–Pliocene Kangtog Formation around the Raggyorcaka area formed isoclinal similar buckle folds, thrust faults and klippen. In the Gangmari–Juhuashan Formation around the Raggyorcaka area formed isoclinal similar buckle folds, thrust faults and klippen. In the Gangmari–Juhuashan Formation around the Raggyorcaka area formed isoclinal similar to the crustal extension with \( \sigma_1 \) subvertical. These studies reveal that \( \sigma_1 \) became subvertical due to the thickened crust, which may easily make conjugate strike-slip fault systems develop within the central Plateau.

There are a series of ENE-trending sinistral strike-slip faults inside the Qiangtang basin, which are associated with the NNE-trending pull-apart basins (Yin et al. 1999; Yin 2000). The Tibetan Plateau extruded eastward along the path of the Bangong–Nuijiang suture zone, and the NE–SW-trending left-lateral strike-slip fault on the north side and the NW–SE-trending right-lateral strike-slip fault on the south side of this suture formed a conjugate fault zone (Yin & Harrison 2000; Taylor et al. 2003).

Ratschbacher et al. (2011) found NW-trending faults north of the above suture usually bear a composite kinematics of both normal and dextral strike-slip. These north–south-trending pull-apart basins and rifts to the north of the Qiangtang basin formed at 8–4 Ma (Yin 2000; Yin & Harrison 2000). Li et al. (2001) concluded that the Shuanghu graben is composed of Pliocene synsedimentary normal faults. Taylor et al. (2003) suggested that the faults in the Qiangtang basin and north–south-trending rifts in southern Tibet occurred at 14–8 Ma. Ratschbacher et al. (2011) discovered that these sinistral strike-slip faults in Qiangtang basin formed during c. 18–7 Ma and were overprinted by active high-angle normal faults starting at c. 5 Ma. These active brittle high-angle normal faults reflect that the strain concentration is weak in the uppermost crust (Ratschbacher et al. 2011). These geochronological results imply that the initiation of the episode II occurred since c. 18 Ma.

East–west-trending upright buckle folds in Neogene and Quaternary sediments superimposing on the earlier north–south-trending buckle folds appear to be inconsistent with the strike-slip stress field of episode II. In light of Cenozoic sediments always exhibit semi-consolidated features, we thus speculate that a decoupled slipping surface existed between upper loose sediments and the lower solid crust. Under this tectonic plane, strike-slip fault systems easily developed, while upright buckle folds are distributed in the above new sedimentary layers (Fig. 8).

Conclusions

The deformations of the North Qiangtang terrane after the Mesozoic is closely related to the collisional tectonics of the Tethys Ocean, which is characterized by intraplate structures of shallow–superficial level forming during the Late Triassic, Early Cretaceous and Cenozoic.

The Mesozoic structural style of this region is dominated by Early Cretaceous horizontal contractional deformations in terms of NW–SE-trending thrust faults preceded by early-formed folds and their fold-accommodation faults. These folds and thrust faults superimposed on Late Triassic NE–SW-trending buckle folds. Thrust faults appear as footwall ramps in outcrop, and their fault zones feature penetrative cleavage or arrangement of giant tectonic
lens-shaped bodies. Rock strata in the hanging wall of these thrust faults were thrust in a NE or NW direction, truncated football layers, and developed anticline or syncline fault-bend folds.

The North Qiangtang terrane demonstrated strong tectonic responses to the Cenozoic tectonic uplift of the Tibetan Plateau. There was a distinct change in deformation mechanisms, allowing the Cenozoic deformations of this terrane to be divided into two stages. Episode I is the north–south horizontal contractional stage (50–40 to 18 Ma–present day); during this episode, buckle folds and thrust faults were aligned in a nearly east–west direction, the thickness of the crust gradually increased, and the Qiangtang basin was gradually uplifted. Episode II is the strike-slip and passive extension stage (18 Ma); during this time, conjugate strike-slip fault systems associated with pull-apart basins were formed. North–south-trending buckle folds associated with extrusion tectonics were developed in the middle and eastern portions of the Qiangtang basin, which were superimposed by WNW–ESE-trending uprise buckle folds.

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