Structural sequence and geochronology of the Qomo Ri accretionary complex, Central Qiangtang, Tibet: Implications for the Late Triassic subduction of the Paleo-Tethys Ocean

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ABSTRACT

The Late Paleozoic Qomo Ri Accretionary Complex (QRAC) in the Central Qiangtang region of Tibet lies at the southern margin of the Longmu Co–Shuanghu suture. QRAC is tectonically linked with the Nierong and Jitang metamorphic complexes in eastern Tibet and the Yunling and Lancang complexes in western Yunnan province, SW China. This metamorphic complex is mainly composed of Late Paleozoic passive continental margin-al strata of the South Qiangtang basin, which was underthrust beneath North Qiangtang in the Late Triassic. At least three stages of deformation, D1, D2 and D3, with two corresponding metamorphic events, M1 and M2, were identified within the QRAC. D1 is characterized by a penetrative foliation, S1, bearing a dextral shear and a corresponding M1 mineral assemblage of phengite, garnet and quartz. This deformation was interpreted to be the result of the northwestward oblique subduction of the Paleo-Tethys Ocean and dated at 211–219 Ma by phengite 40Ar/39Ar ages. D2, a subsequent compression deformation, followed D1 immediately and exhibits flexural folds and pervasive axial crenulation in foliation S2. Deformations from D1 to D2 indicate that an oblique oceanic subduction was immediately followed by a collision between the North and South Qiangtang blocks along the Longmu Co–Shuanghu suture. The D3, recorded by minor folds and divisional axial cleavage (S3), is related to a giant arc structure with an extension of ~50 km.

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1. Introduction

The North and South Qiangtang blocks are regarded as being contiguous with the Sibumasu terrane to the south and as having formed part of the Cimmerian continental strip that separated from northeast Gondwanaland in the late Early Permian (Metcalf, 2006, 2011). New constraints on the configuration of the Paleo-Tethys Ocean in the Tibetan Plateau during the early Late Paleozoic suggest that a branch ocean separating the Western Qiangtang terrane and the Lhasa terrane from the Gondwana continent may have existed during the Late Devonian and the Early Carboniferous (Dai et al., 2011). The Nadi Kangri volcanic rocks, with nearly E-W-trending outcrops within the Qiangtang basin, were also proven to be Late Triassic rift-related volcanic rocks (Fu et al., 2010). Therefore, work on the evolution of the Paleo-Tethys Ocean (Ishida and Hirsch, 2011), especially that including the Central Qiangtang Area, is significant.

The subduction and closure of the Paleo-Tethys Ocean are recorded by the presence of a >500-km-long east–west-trending belt of metamorphic complexes in Central Qiangtang (Kapp et al., 2000, 2003). The Qomo Ri metamorphic complex (QRC) in Central Qiangtang lies to the south of the Longmu Co–Shuanghu suture and to the north of the Bangong–Nujiang suture (Fig. 1A, B). Recently, the tectonic origins and evolution of these complexes have been intensively debated, and several explanatory models were proposed, including the following: (1) an E-W-trending Late Paleozoic continental rift (Wang et al., 1987; Deng et al., 1996); (2) an Indosinian Longmu Co–Shuanghu suture that was formed in association with the subduction of the Paleo-Tethys (Li, 1987, 2008; Liu et al., 2002; Zhang et al., 2005), as well as the Gondwana, (1985); (3) Paleo-Tethys metamorphic complexes are present as the basement of the Qiangtang basin and can be separated into Triassic, Middle Proterozoic metamorphic complexes formed during the subduction of the Paleo-Tethys Ocean (Wang et al., 2009).

Although there remains a series of problems such as the suture’s location and extension, subduction polarity and tectonic evolution,
many common views also exist. Several studies reported that the metamorphic complex in the Qomo Ri area possesses the basic characteristics of a mélange (Kapp et al., 2000, 2003; Wang et al., 2009). The Qomo Ri metamorphic complex presents a wide-exposed flysch matrix enclosing blocks of various tectonic facies such as ophiolite, high-pressure metamorphic rocks, and radiolarian-bearing silicalites. These lithological slices usually manifest lithologies, paleobiologies, and detrital zircon similar to those of the Gondwana-derived terranes to the south (Li, 1987, 2008; Liu et al., 2002).

Our study focuses on the structural style, deformation and metamorphic sequence of the QRAC. Additionally, a new model is proposed to explain the closure process of the Paleo-Tethys Ocean.

2. Geological background

The Qomo Ri area is located in the "Central Qiangtang dome" and exhibits a series of nearly east–west-trending, fan-shaped thrusts and closed buckle folds (Lei et al., 2001). According to previous research, the possible existence of a Middle Proterozoic metamorphic basement was negated, and the Gemuri, Guoganjianianshan and Mayigangri groups are reinterpreted as being mainly composed of Carboniferous–Permian epimetamorphic flysch (Institute of Geological Survey, Jilin University, 2005; Li, 2008). Additionally, hornstone-bearing Ordovician–Devonian strata and a Permian ophiolite with a good sequence were discovered (Institute of Geological Survey, Jilin University, 2005). Based on our detailed field work, the Qomo Ri metamorphic complex consists of 6 lithological units according to the observed tectonic facies, as follows: (1) deep sea-bathyal terrigenous flysch, (2) seamount block, (3) fondothem, (4) oceanic crust relic, (5) Early Paleozoic exotic block, and (6) high-pressure metamorphic rocks (Wang et al., 2009).

The Qomo Ri metamorphic complex is accordingly classified into five main tectonic slices according to their ages, lithologies and degrees of metamorphism (Fig. 2). They all show similar structural styles and contact each other in ductile shear zones. In general, the eastern tectonic slices overlay the western slices in order.

3. Structural style of the Qomo Ri complex

At least three stages of deformation, D1, D2 and D3, and two related metamorphic events, M1 and M2, were identified within the Qomo Ri metamorphic complex. Although D1/M1, D2/M2 and D3 exhibit variable levels of development in the Heishishan, Lanling and Tashishan areas (Fig. 2), the deformational features are similar.

Because outcrops can be clearly observed in Heishishan, Lanling and Tashishan, detailed field work was focused on these three sites. The occurrences of these outcrops are described individually and comprehensively compared.

3.1. D1 deformation

The metamorphic complex in the Heishishan area is composed of a strongly deformed metasedimentary matrix that encloses nearly north–south-trending, less-deformed tectonic blocks of various tectonic facies such as seamount block including basalt and limestone, ophiolite relic and competent quartz sandstone layers. This complex clearly exhibits the earlier two phases of deformation (D1 and D2), where D1 shaped the structural geometry (Fig. 3). Ophiolite relics, such as basalts and gabbros, are usually deformed like rigid bodies and exhibit obvious deformation partitioning, where the less-deformed central part is enwrapped by a fringe fine-schistened zone (Fig. 4A and B). The long axes of the blocks are compatible with the strike of the S1 shear crenulation cleavage. Limestone layers bearing a weak competence usually display a strong rheology and record the structural trace of D2 very well. These layers formed many tectonic boudinages and rootless folds possessing incrassate hinge zones and greatly stretched limbs. The flysch matrix consists of pelite and sandstone exhibiting strong pressolution during deformation. The pervasive S1 foliation has thoroughly overprinted the S0 bedding.

Fig. 1. A: Regional geological map of the Qomo Ri area. B: Geotectonic setting of the Qomo Ri area. Major sutures: JSS, Jinshajiang suture; LSS, Longmu Co-Shuanghu suture; BNS, Bangong–Nujiang suture; YZS, Yarlung Zangbo suture. Abbreviations: I, Gemuri–Qomo Ri metamorphic complex; II, Nierong metamorphic complex; III, Jitang metamorphic complex; IV, Yunling metamorphic complex; V, Lancang metamorphic complex.
The \( S_1 \) foliation always displays fine schistosity zoning in which the microlithons, syntectonic quartz veins, are divided by oriented sericite stripes. The Lanling high-pressure metamorphic complex is mainly composed of blueschist, garnet–phengite–quartz schist and marble that exhibit three distinct stages of deformation (\( D_1, D_2, \) and \( D_3 \)). Although showing the complicated structural superimpositions of these deformations, the first simple shear (\( D_1 \)) preserves its geometry well and dominates the general structural style. \( D_1 \) shows a strong rheology in the HP/LT rocks and a pervasive \( S_1 \) crenulation cleavage bearing a dextral shear (Fig. 5B). These rocks were all intensely folded, elongated and even broken up to become oriented in a nearly north–south direction. In the outcrop, blueschists and marbles overlap each other alternately and occur repeatedly in the transverse direction, indicating a complete structural transposition of \( D_1 \) (Fig. 5A). Marbles also formed many similar folds on the scale of 10–100 m, which were then elongated to become rootless folds and boudinages under progressive shear. Schists bearing the minerals garnet, phengite, and quartz grew many garnet porphyroblasts that well recorded the kinematics of \( D_1 \). These garnets usually exhibit good \( \sigma \)-shapes, bearing asymmetric quartz tails that indicate a dextral simple shear. Microscopic studies revealed that these garnets are syntectonic porphyroblasts of \( D_1 \). The inner rectangular quartz bands are consecutive with the external ones, together displaying “\( Z \)” shapes, which also imply the dextral shear of \( D_1 \).

The rock assemblage in the Tashishan area is similar to that in Heishishan and mainly consists of a Late Paleozoic epimetamorphic but intensely schistified flysch matrix. The matrix encloses blocks of Early Paleozoic exotic metasedimentary, Middle Permian carbonatite and basic magmatic rocks. Generally, all these blocks contain the surrounding rocks in ductile shear zones and were stretched in a nearly E–W direction. After examining the outcrop and the microscopic analyses, we concluded that this area clearly exhibits the aforementioned three stages of deformation. The \( D_1 \) bearing dextral shear formed the E–W-trending tectonic trace and the penetrative \( S_1 \) foliation, which was later thoroughly overprinted by the regional \( S_2 \) foliation.

The \( D_1 \) deformation is well preserved, especially in shallow marine limestones, which commonly exhibit intense ductile shear and form classic S–L tectonic rock bearing a stretching lineation and A-type folds. In the contact zone of basalt and limestone, this dextral shear initiated intense structural transposition and formed classic mylonites possessing S–C fabrics (Fig. 6A). Rigid basalt was splintered and elongated into rotated porphyroclast bearing asymmetric calcite tails. Recrystallized limestone usually exhibits directed lathy bands as a result of strong stretching. The systematic statistical analysis of the \( L_1 \) lineation in \( S_1 \) in these mylonites revealed that the shear foliation \( S_1 \) moderately dips to the northeast or southwest, whereas the lineation \( L_1 \) plunges to the WNW or ESE, respectively, at lateral angles of less than 30° (Fig. 6C). The alternating dip direction of foliation \( S_1 \) is related to the \( D_2 \) superimposition of flexural folding, which was observed in the outcrop.

### 3.2. \( D_2 \) deformation

In the Heishishan area, \( D_2 \) is characterized by compression deformation recorded by flexural-slip folds. Competent layers such as rigid basalt blocks formed open anticlines, while the limestones or metasediments in their limb areas experienced interlayer sliding and formed many asymmetric S- or Z-shaped subsidiary folds (Figs. 3 inset C and 4C, D). Sericite phyllites metamorphosed from clastic and mafic rocks exhibit asymmetric multi-ordered minor folds, forming an \( S_2 \) penetrative cleavage crenulation that largely replaced \( S_1 \). The dip direction of the \( S_1 \) foliation alternates and varies transversely in the outcrop. Its intersection exhibits a preferred orientation that coincides with the projection of a minor fold hinge of \( D_2 \) in the Wulff net. Crystalline limestone layers occasionally exhibit superimposed folds, in which the open anticlines of \( D_2 \) overlay the reclined, rootless and isoclinal folds of \( D_1 \). S- or Z-shaped asymmetric folds bearing horizontal hinges often occur in these open flexural folds of \( D_2 \).

In Lanling, \( D_2 \) is characterized by parallel or symmetric buckle folds (Fig. 5C). These folds always bear N–S axial directions and are...
superimposed on the inclined shear folds of D1. Schistose rocks such as blueschist and phengite schist typically exhibit many subsidiary folds with multi-ordering. Foliation S1 has deformed to form Z- or S-shaped asymmetric folds and is locally replaced by axial crenulation cleavage S2 (Fig. 5D).

D2 is also well developed in Tashishan, exhibiting upright horizontal folds at ~60 m in recrystallized limestone layers with an open hinge zone. Epimetamorphic clastic rocks such as phyllites and quartz sandstone bearing a pervasive S1 foliation mostly form minor folds of ~10 cm due to the thin layers and weak competence (Fig. 6B). In the outcrop, the quartz veins precipitated as microlithons in S1 and formed abundant and similar miniscule folds as the hinge zone gradually became incrassate and the limbs were intensely stretched. Consequently, a new foliation, S2, occurred within the neogenesis sericite and chlorite as a result of intense pressolution in limb areas. Across the Tashishan area, S2 broadly spreads in these clastic rocks, with a stable occurrence that dips moderately NE. The minor folds of D2, however, display a random preferred orientation in the Wulff net (Fig. 6D).

3.3. D3 deformation

D3 is well developed in both Lanling and Tashishan, exhibiting gentle folds or small flexural folds of 0.1–2 m. These small folds are usually superimposed on the asymmetric folds of D2 to create a composite geometry. In sericite phyllites or phengite schists, the folds always occur as superimposed crenulation due to the fairly thin schistosity (Fig. 10B). The divisional axial cleavage S3 emerges locally in the hinge zones of these folds and is sub-parallel to the axial plane.

3.4. Deformation and metamorphic sequence

Generally, the Qomo Ri complex exhibits three distinct phases of deformation; the earlier two were accompanied with intense
metamorphism. D1 displays a clear dextral shear at the middle-lower tectonic level, which initiated a succeeding thorough oblique structural transposition and formed the regional E-W- and N-S-trending tectonic belts. D1 formed a penetrative crenulation cleavage S1 and is characterized by similar or root-less folds and tectonic boudinages. D2 shows a clear compression deformation at the upper tectonic level, which formed many open flexural folds of ~30 m, small-scale thrust faults and a pervasive crenulation cleavage S2 parallel to the axial plane of these buckle folds. D3 mainly displays crenulations and small-scale flexural folds.

3.4.1. The D1 deformation and the M1 metamorphism

D1 forms a pervasive crenulation S1, which exhibits a clear dextral shear and completely overprinted the original sequences of these lithological blocks in the QRC. Similar structural features were observed in the above three areas in that every lithology unit experienced an

**Fig. 4.** Deformation features of the Heishishan ophiolite mélangé slab ((C–P2) H). A and B show the dextral shear of D1, and C and D reveal the compressional deformation of D2. A: A typical deformation partition in a basalt. B: A rotational calcite porphyroclast in a strongly schistized basalt. C: A parallel anticline in a basalt. D: Buckle folds in recrystallized limestone.

**Fig. 5.** Structural characteristics of the Lanling HP-metamorphic rocks ((C–P2) L). A and B show the dextral shear of D1, and C and D reveal the compressional deformation of D2. A: Stacking sequence of marble and blueschist exhibiting thorough transpositions of simple shear. B: Strong rheology in the marble–blueschist contact zone. C: An open anticline of garnet-bearing blueschist. D: Foliation replacement, where S2 pervasively overprinted S1.
intense simple shear deformation in ductile conditions. Additionally, the metamorphic facies of D1 in the Tashishan and Heishishan area are the same low-middle greenschist facies, which is obviously lower than the high greenschist facies of the Lanling HP metamorphic rocks.

In Heishischen, S–L tectonic rocks are usually well developed in the contact zone of limestone and basalt, with clear S–C fabrics (Fig. 7A). Rigid basalt mainly exhibits σ-shaped porphyroclasts bearing asymmetric calcite tails, whereas calcite in limestone formed elongated, lathy stripes. On the microscopic scale, calcites were also intensely stretched to become oriented ribbons (Fig. 7B). After strain measurements of these ribbon-like calcites from oriented thin-rock slices, the finite strain ratios along the three principal strain axes were determined to be $X/Z \approx 8.27$ and $Y/Z = 2.15$ (Fig. 8). Accordingly, the k value of the Flinn diagram is 2.48, which indicates that the finite strain ellipsoid of D1 exhibits long-body flaser type. Epimetamorphic flyschs universally display the penetrative foliation $S_1$ subparallel to...
the bedding plane $S_0$, which suggests a strong contraction ratio during $D_1$. Additionally, as a result of pressolution, these clastic rocks demonstrate an intense metamorphic differentiation. Flaky minerals such as sericite and chlorite, arranged linearly to constitute cleavage domains as quartz and calcite dissolved, migrated and filled between these cleavage domains in the shape of veins. Moreover, these quartz veins experienced progressive deformation during $D_1$ and usually show core–mantle structures consisting of subgrains and dynamic recrystallized grains.

The structural and metamorphic features of the E–W-trending tectonic belt in Tashishan are similar to those in the Heishishan area in terms of the S–L tectonic rock and syntectonic quartz veins. Furthermore, these two areas bear the same neogenic mineral assemblage of $D_1$: Ser + Qtz + Chl + Cal ± Bt.

The Lanling HP metamorphic rocks exhibit geometries and kinematics analogous to those of the Heishishan ophiolite mélangé and formed many NW–SE-trending marble rootless folds or boudinages. These rocks also exhibit a strong ductile shear and the foliation $S_1$. In the garnet-bearing blueschist, glaucophane was arranged in an orderly manner to constitute the $S_1$ foliation as the rigid garnets were flasered and rotated, exhibiting as porphyroblast. The phengite–quartz schists display the $S_1$ foliation well and developed many o-shaped garnet porphyroblasts (Fig. 7C). There is a consensus that this porphyroblast contains much valuable information concerning simultaneous or later deformation and metamorphism, facilitating the study of metamorphic facies and structural kinematics (Bell, 1985; Johnson, 1999; Williams and Jiang, 1999; Passchier and Trouw, 2005). After many structural analyses of these garnet porphyroblasts, both in the outcrop and by microscopic observations, we inferred that they are all syntectonic porphyroblasts formed during the first shear ($D_1$). Typically, they display vimeinous asymmetric quartz tails intersecting foliation $S_1$, indicating a clear dextral shear. Furthermore, these porphyroblasts always contain abundant band-like quartz inclusions that are rotated clockwise, exhibiting “Z” shapes along with those in the asymmetric tails (Fig. 7D). Overall, the Lanling HP metamorphic rocks present a neogenic mineral assemblage of $D_1$ as follows: Ph + Qtz + Grt + Cal + Bar.

3.4.2. The $D_2$ deformation and the $M_2$ metamorphism

After $D_1$, the Qomo Ri complex was gradually exhumed to an upper crustal position and developed clear compressional deformations including flexural folds and small-scale thrust faults. These upright-buckle folds are usually superimposed on the inclined plunging folds of $D_1$ to display a composite geometry (Fig. 9A and B). Our statistical analysis revealed that the fold axes exhibit a preferred orientation that plunges gently to NE 10°–20° in Heishishan and Lanling but to 120° in Tashishan. Additionally, multiple-order subsidiary folds of 0.05–10 m usually develop in the limbs and bear asymmetric “Z” or “S” shapes. In Heishishan, the axes of these minor folds possess an obvious preferred orientation that plunges very gently to either NW 350° or SE 170°, which generally matches the intersection of $S_1$. However, the axes exhibit a more complicated preferred orientation in Tashishan that plunges gently NW or NE while the axial cleavage crenulation $S_2$ remains very stable.

$D_2$ initiates an intense horizontal compression in all three areas and develops a regional $S_2$ foliation that thoroughly replaced $S_1$ in the Heishishan and Tashishan areas. The $S_2$ foliation is exhibited quite well in metamorphic clastic rocks such as phyllite and quartz sandstone. Whether on the outcrop or at the microscopic scale, pervasively distributed quartz veins, the microlithons of $S_2$, form continuous symmetric minor folds bearing closed hinge areas (Fig. 9C). Under progressive coaxial compression, these recrystallized veins show an intense contraction, where the hinges were gradually thickened to become rootless, whereas the limbs experienced strong stretching and pressolution to enrich undissolved minerals such as sericite (Fig. 9D). As a result, these residual mineral were usually recrystallized and directionally aligned to make up the cleavage domain of $S_2$.

Overall, $D_2$ shows a metamorphic degree of sub-low greenschist facies and possesses a neonatal mineral assemblage consisting of sericite and chlorite. Nevertheless, $D_2$ locally displays much lower metamorphic facies and few neogenic minerals.

3.4.3. The $D_3$ deformation

The last deformation ($D_3$) commonly manifests as a shallow tectonic level. The sericite phyllites in Tashishan exhibit plentiful $D_3$ crenulation folds on the $S_2$ plane. The $S_2$ foliation also demonstrates many buckle folds of 10–40 cm and sparsely nonpenetrative axial $S_3$ cleavage with a fan-like geometry (Fig. 10A). Utilizing systematic statistics on the attitudes of $S_3$ and the axes of $F_3$, we discovered that the $S_3$ foliation dips steeply to the NW or SE and that the axes of the relevant folds plunge gently to the NE (Fig. 10C, D). In the Lanling area, phengite quartz schists usually display crenulation fold cleavages of ~5 mm, superimposing the minor buckle folds of $D_3$ on the crenulations of $D_2$ (Fig. 10B).

Notably, the E–W-trending tectonic belt in Tashishan shows analogous lithological assemblages, deformation features and metamorphic facies as the N–S-trending tectonic belt of Heishishan. These belts both show the same structural style and metamorphism with respect to $D_1$ and $D_2$, which probably means that they had identical geometries and kinematics before $D_3$. Additionally, after a large-scale mapping, we concluded that these belts comprise a clear regional arc structure of ~50 km with a very open hinge area. Both in Qomo Ri and Gangtang Co, it is obvious that the trending directions of tectonic slices such as schistose basaltis or blueschists (C–P1 L) and carbonates (P2 L) turn smoothly from E–W to N–S. This arc structure exhibits a NE–SW trending axis coinciding with those of the minor or crenulation folds of $D_3$ quite well, implying that they were probably formed together during $D_3$.

Yibuchaka demonstrates two fine rhombuses, which definitively indicate a left-lateral shear zone. It has been reported that the left-lateral active Yibuchaka fault extends in an S shape for up to ~340 km and consists of a series of steeply dipping normal faults (Taylor et al., 2003). In the map view, this active left-slip fault clearly...
truncates the N–S-trending tectonic belt and the regional arc structure, which also clearly indicates a syntectonic reverse drag fold.

4. **40Ar/39Ar geochronology**

4.1. Methods

Two samples (P22-16-TW1 and P22-16-TW3, both collected at Lanling) from the Qomo Ri complex were selected for phengite separates. Both samples were fresh and contained phengite suitable for 

\(^{40}\text{Ar}/^{39}\text{Ar}\) dating. The samples were crushed, washed in distilled water in an ultrasonic bath for 1 h, and then dried. Phengite separates (1–2 mm long) were handpicked under a binocular microscope. Mineral separates were irradiated along with monitors of the Fish Canyon sanidine (28.02 Ma; Lamphere and Baadsgaard, 1997) and ZHB biotite (133.3 Ma; Fu et al., 1987) for 9 h at the radiation center at the Institute of Atomic Energy of China. After two months of cooling, 32–34 mg of phengite separates from each sample were analyzed by incremental heating employing an MM-5400 mass spectrometer at Peking University. Argon gas was

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**Fig. 9.** The structural and metamorphic features of D2/M2. A and B show composite folds from Heishishan and Lanling, respectively. C and D present foliation replacements, both on the outcrop and at the microscopic scale.

**Fig. 10.** Characteristics of D3. A: Small buckle folds of D3 and axial cleavage S3 in epimetamorphic fysch. B: Cross-folds where F3 crenulation folds are superimposed on F2 crenulation folds in phengite–quartz schist from Lanling. C: Stereographic polar projection of S3 in the Tashishan area (lower hemisphere). D: Contour diagram for the axes of the F3 minor folds in Lanling.
extracted at consecutively higher temperatures for 10 min at each designated temperature. Measured argon isotope peak heights were extrapolated to zero time, normalized to the $^{40}\text{Ar}/^{36}\text{Ar}$ atmospheric ratio (295.5) using measured values of atmospheric argon, and corrected for neutron-induced $^{40}\text{Ar}$ from K, for $^{39}\text{Ar}$ and $^{36}\text{Ar}$ from calcium, and for $^{36}\text{Ar}$ from chlorine (Onstott and Peacock, 1987). The values for the reactor correction factors are $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}=0.000271$, $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}=0.000652$, and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}=0.00703$. The $J$ factor used in the age calculation is 0.001747. Soft Isoplot 3.0 was used for the calculation of plateau ages and isochron dating (Ludwig, 2003).

4.2. Results

We also selected a fine sample of phengite quartz schist in Lanling to conduct $^{40}\text{Ar}/^{39}\text{Ar}$ dating on phengite grains and acquired two reliable plateau ages of 219.1±1.4 Ma and 211.9±1.2 Ma for phengite (Fig. 11). The analytical results are listed in Table 1 and illustrated in Fig. 11. All data reported are quoted at 1σ error, which includes the analytical uncertainties of the monitor analyses ($J$-values), but the error for the age of the monitor was assumed to be zero. In this study, age plateaus are defined using the criteria of McDougall and Harrison (1999), where three or more consecutive steps, corresponding to at least 50% of the total $^{39}\text{Ar}$ released, yield apparent ages reproducible at the 95% confidence level.

The analyzed samples yielded well-defined plateau ages of 219.1±1.4 Ma and 211.9±1.2 Ma (Fig. 11). Samples P22-16-TW1 and P22-16-TW3 have isochron ages of 218.2±1.3 and 212.4±1.3 Ma, which are consistent with the corresponding plateau ages to within the analytical uncertainty.

5. Discussion

As described above, Qiangtang is divided into North and South Qiangtang blocks bearing two distinct paleogeographic provinces by the Paleo-Tethys during the Late Paleozoic (Li, 1987, 2008; Liu et al., 2002). The North and South Qiangtang blocks have two distinguishable paleogeographies of Cathaysian affinity and Gondwanan affinity, respectively (Li, 1987, 2008; Liu et al., 2002). Moreover, the complex in the Tashishan area comprises a tectonic slice of early Paleozoic sedimentary layers bearing typical Gondwanan fauna (Institute of Geological Survey, Jilin University, 2005; Li, 2008). Herein, the discussions are focused on the dynamic process during the subduction of the Paleo-Tethys Ocean and the formative mechanism of these Central Qiangtang metamorphic complexes including the QRC.

5.1. D2 immediately following D1

The geochronology of the Central Qiangtang metamorphic belt including the Lanling HP metamorphic complex has been intensively studied. Many reliable phengite plateau ages have been obtained, e.g., 221.8±0.1 Ma in Lanling (Kapp et al., 2003), 217.2±1.8 Ma in Pianshishan and 219.3±1.5 Ma and 215±2 Ma in Lanling (Li et al., 2006), and 214.1±1.8 Ma, 219.5±1.7 Ma and 223.2±1.7 Ma in Gemuri (Zhai et al., 2009, 2011).

![Fig. 11. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages and isochrons of phengite from quartz–phengite schists in Lanling.](image-url)
folds and minor fold axes in the D2 are in the NNW or N directions, the middle strain axis of D2 would display a NW orientation, which coincides with that of D1. Similarly, in the N–S-trending tectonic belt of the Tashishan, L1 plunges to the ESE-trending Longmu Co–Shuanghu suture. The Indosinian Longmu Co–Shuanghu suture separating the North and South Qiangtang terranes has been hypothesized to exist in central Qiangtang and possess a northward subduction polarity (Li et al., 1995; Zhang et al., 2006; Zhang and Tang, 2009). The above hypothesis is mainly based on studies of stratigraphy and magma arc. Our new model emphasizes the structural analyses of the Qomo Ri complex and describes its underthrusting polarity as follows.

### 5.2. Tectonic implications for the subduction of the Paleo-Tethys Ocean

The Indosinian Longmu Co–Shuanghu suture separating the North and South Qiangtang terranes has been hypothesized to exist in central Qiangtang and possess a northward subduction polarity (Li et al., 1995; Zhang et al., 2006; Zhang and Tang, 2009). The above hypothesis is mainly based on studies of stratigraphy and magma arc. Our new model emphasizes the structural analyses of the Qomo Ri complex and describes its underthrusting polarity as follows.

### 5.3. Implications for the accretionary tectonics of the Paleo-Tethys

The accretionary orogen is a new orogen type that was first proposed in the 1990s (Sengör et al., 1993). Several models have been used to explain the dynamics of the accretionary orogen and accretory complexes including the retrogradation of tectonic meanders and the subduction–accretionary mechanisms of the arc-trench systems (Xu et al., 1994; Xiao et al., 2002, 2005, 2010; Li, 2004; Cawood and Buchan, 2007; Pan et al., 2008; Yuan et al., 2009). It is commonly acknowledged that (1) accretionary complexes consist of different

## Table 1

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<th>T(°C)</th>
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<td>900</td>
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Additionally, the blueschists and eclogites usually exhibit slightly greater 40Ar/39Ar ages, e.g., 222.5 ± 3.7 Ma for glaucophane at Naruo (Zhai et al., 2009). Because these HP metamorphic rocks of different ages were all involved in the same deformation, a coherent deformation process is observed. Based on the above discussions, D1 and D2 represent two coherent stages of subduction and collision, respectively. Although the Late Paleo-Tethys flysch and intracontinental magmatic rocks of the South Qiangtang block constitut the Qomo Ri complex, and their sedimentary bedding S0 mainly experienced two phases of structural superimposition. However, the Late Paleo-Tethys strata of the North Qiangtang block preserve their original sedimentary sequence and were conformably overlaid by Mesozoic strata. Furthermore, the Late Paleo-Tethys strata display brittle faults and parallel flexural folds. The above details suggest that the Paleo-Tethys was probably underthrust northward beneath the North Qiangtang terrane, resulting in the later underthrust of the South Qiangtang passive continental margin. Thereby, the suture of the Paleo-Tethys Ocean should be located to the north of the exposures for the Late Paleo-Tethys strata of the North Qiangtang terrane, which basically accords with the location of the NW–NE-trending Longmu Co–Shuanghu suture. The carbonate mylonites exhibit a clear S1 shear foliation and an L1 mineral stretching lineation that formed during the subduction of the Paleo-Tethys. Interestingly, these shear structures are indicative of the geometry and kinematics of this dynamic process. In the outcrops, S1 has been deformed to form upright open folds of 10–30 m. In the E–W-trending tectonic belt of the Tashishan, L1 plunges to the ESE-trending Longmu Co–Shuanghu suture. The Indosinian Longmu Co–Shuanghu suture separating the North and South Qiangtang terranes has been hypothesized to exist in central Qiangtang and possess a northward subduction polarity (Li et al., 1995; Zhang et al., 2006; Zhang and Tang, 2009). The above hypothesis is mainly based on studies of stratigraphy and magma arc. Our new model emphasizes the structural analyses of the Qomo Ri complex and describes its underthrusting polarity as follows.

### 5.2. Tectonic implications for the subduction of the Paleo-Tethys Ocean

The Indosinian Longmu Co–Shuanghu suture separating the North and South Qiangtang terranes has been hypothesized to exist in central Qiangtang and possess a northward subduction polarity (Li et al., 1995; Zhang et al., 2006; Zhang and Tang, 2009). The above hypothesis is mainly based on studies of stratigraphy and magma arc. Our new model emphasizes the structural analyses of the Qomo Ri complex and describes its underthrusting polarity as follows.

### 5.3. Implications for the accretionary tectonics of the Paleo-Tethys

The accretionary orogen is a new orogen type that was first proposed in the 1990s (Sengör et al., 1993). Several models have been used to explain the dynamics of the accretionary orogen and accretory complexes including the retrogradation of tectonic meanders and the subduction–accretionary mechanism of the archipelagic arc–basin systems (Xu et al., 1994; Xiao et al., 2002, 2005, 2010; Li, 2004; Cawood and Buchan, 2007; Pan et al., 2008; Yuan et al., 2009). It is commonly acknowledged that (1) accretionary complexes consist of different
tectonic slabs such as accretionary wedges, island arcs, continental crust relics, ophiolite and seamount and (2) these complexes tectonically congregated together, experienced intensely structural transposition and generally exhibit several deformation and metamorphic sequences. Accordingly, we deduced that the Qomo Ri metamorphic complex belongs to an accretionary complex and represents an important tectonic event for the Paleo-Tethys in the Tibetan plateau.

Central Qiangtang is an important area for understanding the early geological evolution of the Tibetan plateau due to its largely exposed metamorphic complex including the QRAC (Kapp et al., 2003; Li, 2008; Wang et al., 2009). Additionally, analogous metamorphic complexes have been discovered in eastern Tibet and western Yunnan (Fig. 1B). The Nierong and Jitang metamorphic complexes in eastern Tibet display lithologies, deformations, and metamorphisms similar to those of the QRAC (Wang et al., 2006, 2008). These complexes also yielded a homochronous plateau 40Ar/39Ar age of 230 ± 1 Ma for phengite. Additionally, Zhao (1994) reported a glaucophane plateau 40Ar/39Ar age of 214 Ma for the Lancang metamorphic complex in west Yunnan. We concluded that this age suggests an intense structural transposition in the complex during the eastward subduction of the Paleo-Tethys. As a result, we suggest that these homogenous complexes are tectonically linked together to constitute a large-scale Indosinian accretionary orogen. Identical 40Ar/39Ar ages and the corresponding subduction polarity imply that these complexes formed in the process of the southward or eastward accretion of the southern Eurasian continent.

Furthermore, the westward extension of the Shuanghu suture remains controversial. One perspective proposes that it merged into the Jinsha suture to the west as a branch suture (Zhang et al., 2006; Dai et al., 2011). The other maintains that it is an independent suture of the Paleo-Tethys and extends westward alone (Li, 2008; Zhai et al., 2011). Xiao et al. (2002, 2005) reported an accretionary complex in west Kunlun that finally accreted northward to the Tarim block 214–220 Ma. These synchronous accretion events in both the Jinsha and Shuanghu sutures equally represent the subduction and closure of the Paleo-Tethys Ocean. For this reason, we also deduced that the Late Carboniferous to Middle Permian Ocean separating the North and South Qiangtang blocks was a minor branch of the Paleo-Tethys, and the Longmu Co–Shuanghu suture is a branch of the primary Jinsha suture.

6. Conclusions

Our model of the accretionary orogen for interpreting the QRAC in Central Qiangtang is based on the following conclusions:

1) The QRAC in central Qiangtang is composed of Late Paleozoic passive continental marginal strata of the South Qiangtang. It exhibits three distinct phases of deformation and two relevant phases of regional metamorphism. The first two phases of deformation and metamorphism occurred during the oceanic subduction of the Paleo-Tethys and shaped the structural style of the QRAC.

2) The first deformation (D1) exhibits a dextral shear and formed the regional E–W- and N–S-trending tectonic belts; its age is constrained to 211–219 Ma by phengite 40Ar/39Ar dating. Both the Heishishan ep metamorphic ophiolite complex and the Lanling HP metamorphic rocks display accordant tectonic traces, reflecting the oceanic subduction is a progressive shear involving rocks on different tectonic levels. The second compressed deformation (D2) emerged on a lower tectonic level and formed the regional foliation Sz2. The third deformation, D3, which is related to the formation of the regional arc structure, mainly exhibits minor folds and nonpenetrative axial cleavage.

3) D3 followed D1 immediately in the process of the northwestward subduction and the closure of the Paleo-Tethys Ocean. The metamorphic complexes in Central Qiangtang and western Yunnan
are typical accretionary complexes that constitute a large-scale Indoasian accretionary orogen.

Acknowledgments

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References


