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Tectonic evolution and high-pressure rock exhumation in the Qiangtang Terrane, Central Tibet

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Abstract

Conflicting interpretations of the > 500 km long, east-west trending Qiangtang Metamorphic Belt have led to very different and contradicting models for the Permo-Triassic tectonic evolution of Central Tibet. We define two metamorphic events, one that only affected Pre-Ordovician basement rocks and one subduction-related Triassic high-pressure metamorphism event. Detailed mapping and structural analysis allowed us to define three main units that were juxtaposed due to collision of the North and South Qiangtang terranes after closure of the Ordovician-Triassic ocean that separated them. The base is formed by the Precambrian-Carboniferous basement, followed by non-metamorphic ophiolitic mélange, containing mafic rocks that range in age from the Ordovician to Middle Triassic. The top of the sequence is formed by strongly deformed sedimentary mélange that contains up to > 10 km size rafts of both un-metamorphosed Permian sediments and high-pressure blueschists. We propose that the high-pressure rocks were exhumed from underneath the South Qiangtang Terrane in an extensional setting caused by the pull of the northward subducting slab of the Shuanghu-Tethys. High-pressure rocks, sedimentary mélange and margin sediments were thrust on top of the ophiolitic mélange that was scraped off the subducting plate. Both units were subsequently thrust on top of the South Qiantang Terrane continental basement. Onset of Late Triassic sedimentation marked the end of the amalgamation of both Qiangtang terranes and the beginning of spreading between Qiantang and North Lhasa to the south, leading to the deposition of thick flysch deposits in the Jurassic.

1 Introduction

The Tibetan plateau is an amalgamation of terranes that were accreted to the southern margin of Eurasia during Phanerozoic times (Yin and Harrison, 2000). From north to south, these terranes are the Qilian Shan, Qaidam, Songpan-Ganzi Flysch Complex, Qiangtang, and Lhasa terranes (Fig. 1a). Terrane boundaries are defined by widely

SED
7, 329–367, 2015

scattered belts of ophiolitic fragments and mélanges with high-pressure rocks (Zhu et al., 2012). These represent to opening and closure of several oceans. However, which ocean subducted where, and in which direction, is still subject of ongoing controversy. For example, Triassic subduction mélange and high-pressure rocks that are exposed in the Qiangtang Metamorphic Belt in Central Tibet are interpreted in radically different ways (Kapp et al., 2003b; Li et al., 2006; Liang et al., 2012; Zhai et al., 2011a; Zhao et al., 2014).

Li et al. (1987) interpreted the blueschists and subduction mélange as the remnants of a Late Triassic suture zone. They proposed that the Qiangtang Terrane was separated into a northern and a southern terrane, separated by the Paleo-Tethys Ocean. As a result of northward subduction of this Paleo-Tethys underneath the North Qiangtang Terrane, high-pressure rocks and subduction mélange were thrusted southward onto the South Qiangtang Terrane (Zhang et al., 2006b; Zhai et al., 2011b; Zhao et al., 2014). The inferred suture between the two terranes is called the Longmu Co-Shuang Hu suture (short "Shuanghu" suture). The alternative to this "overthrust" model is the "underthrust" model of Kapp et al. (2000, 2003b) and Pullen and Kapp (2014), in which the Paleo-Tethys separated a single Qiangtang Terrane in the south and the Songpan-Ganzi Flysch Complex in the north. The Paleo-Tethys subducted to the south underneath the Qiangtang Terrane along the Jinsha Suture (JSS). High-pressure rocks and mélange were subsequently exhumed by core-complex like normal faulting and doming in the middle of the Qiangtang Terrane. To avoid confusion on the names of the various oceans, we use the term "Shuanghu-Tethys" for the ocean that is proposed to have separated the SQT and NQT and subducted at the Shuanghu suture.

The two different models thus predict totally different tectonic histories of central Tibet and, therefore, the initial boundary conditions for Cenozoic growth of the Tibetan Plateau. Here we present the results of detailed mapping and structural reconstruction of the Rongma area in the centre of the Qiangtang Metamorphic Belt. These results support the overthrust model and thus indicate that the north and south of the Qiangtang Terrane were once separated by an ocean that closed in the Late Triassic.

SED
7, 329–367, 2015

2 Regional setting

The Qiangtang Terrane is located in the centre of the Tibetan plateau (Fig. 1a). It extends for more than 1200 km from east to west and reaches a maximum width of ~ 500 km. To southeast of the Tibetan plateau, it connects with the Sibumasu Terrane (Metcalfe, 2009). The Songpan-Ganzi Flysch Complex lies to the north of it, with the Jinsha Suture Zone (JSS) in between (Yin and Harrison, 2000). This suture zone represents the Paleo-Tethys (or a branch of it) between Eurasia and the Qiangtang Terrane that was consumed by southward subduction beneath the Qiangtang Terrane in Late Triassic to Early Jurassic times (Dewey et al., 1988; Nie et al., 1994; Yin and Nie, 1996; Kapp et al., 2003b). The Bangong-Nujiang suture zone (BNS) separates the Qiangtang Terrane from the Lhasa Terrane to the south. It is characterized by a > 1200 km-long east west trending belt of widely scattered ophiolitic fragments that are associated with a thick sequences of mainly Jurassic flysch, mélange, and volcanic rocks (Wang et al., 1983). The belt exhibits an anomalously large across-strike width, especially in far western Tibet between Rutog and Shiquanhe and northwest of Lhasa between Xainza and Amdo (Kapp et al., 2003a).

Some regard the Qiangtang Terrane as a single terrane (Kapp et al., 2003b; Pullen et al., 2011) that, together with the Sibumasu Terrane, separated from Gondwana in Paleozoic times (Metcalfe, 2009). Others divided the terrane into a North Qiangtang (NQT) and a South Qiangtang Terrane (SQT) (Liu et al., 2011; Li et al., 2009). In this model, the two terranes were separated by the Shuanghu suture that closed in Late Triassic times by northward subduction of ocean underneath the NQT. This north-south division will be used throughout this paper. It should be noted that the SQT and NQT are equivalent to the East and West Qiangtang terranes, respectively, of Zhu et al. (2012).

In the SQT, the autochtonous units consist of low metamorphic grade pre-Ordovician basement, unconformably overlain by Middle Ordovician siltstone and Carboniferous flysch and sandstone, including glaciomarine deposits, all with Gondwana affinity (Zhao et al., 2014). Only Late Devonian limestones and Early Carboniferous limestone intercalated with siltstone are exposed on the southern margin of the NQT. Permian sediments are different in the NQT and SQT. In the SQT, only Middle Permian limestones are exposed, characterized by cold-water fauna (Li et al., 1995; Zhang and Tang, 2009). In the NQT, only Late Permian sedimentary rocks are found, comprising sandstone, mudstone and limestone with abundant warm-water fusulinid and coral fossils of Cathaysian affinity (Li et al., 1995; Zhang and Tang, 2009). Lower to Middle Triassic sediments are only found on the southern margin of the NQT (Fig. 1b). These are bathyal sediments including fossiliferous limestone, massive limestone, oolitic limestone and minor intercalated sandstone and siltstone layers.

Late Triassic terrestrial sediments, limestones and volcanics are the first post-collisional deposits in both the SQT and NQT. Magmatic arc volcanics dominate on the southern margin of the NQT (Zhai and Li, 2007; Zhai et al., 2012), whereas the occurrence of limestone increases towards the south. During the Jurassic, marine sediments were deposed on both the SQT and NQT, while Cretaceous limestones are only found on the SQT (Kapp et al., 2005). Tertiary, and possibly also late Cretaceous, conglomerates unconformably overlie all above rocks in intramontane, fault bounded basins (Kapp et al., 2005).

High-pressure rocks, including blueschists and eclogites, as well as subduction mélange with ophiolitic fragments are found scattered over a > 500 km long, EW-striking belt in the middle of the Qiangtang Terrane: the Central Qiangtang Metamorphic Belt (Kapp et al., 2003b; Liu et al., 2011; Zhang et al., 2006a). Ar-Ar analyses on synkinematic phengite and zircon Lu-Hf isotopic ages from high-pressure units yielded ages from 244 Ma to 214 Ma (Pullen et al., 2008; Zhai et al., 2011b), which is interpreted to provide an estimate for the age of suture zone closing (Li et al., 2009) as well as exhumation of the high-pressure rocks. These ages coincide with those of granitoids in the Qiangtang Terrane, which range in age from 234 Ma to 177 Ma (Zhang et al., 2011). Only one Late Triassic granite, the ~ 210 ± 4 Ma Gangtang Co granite (Kapp et al., 2003b) is found in the SQT within the study area. This large, undeformed granite

SED
7, 329–367, 2015

intruded both mélange and basement rocks (Kapp et al., 2003b; Zhao et al., 2014). This granite thus marks the end of collisional activity and is approximately coeval with volcanic deposits in the NQT and the SQT.

Based on the brief overview above, the rocks in the Qiangtang Terrane can be divided into three groups. Autochtonous continental crustal rocks older than the Late Triassic ocean closure, including pre-Ordovician basement rocks and overlying Ordovician to Triassic units. Units deposited after closure, including the Gangtang Co granite, form the second autochtonous series. These range from the Late Triassic sediments and volcanics to recent terrestrial deposits. The third group is formed by the mélange and high-pressure rocks, and which also includes blocks and rafts of the older autochtonous series rocks.

The two conflicting models make testable predictions on stratigraphy, metamorphic grade and structural relationships between the different rock units in the study area. These are briefly discussed here. This is followed by a more detailed overview of the stratigraphy in the critical period from the Permian to the Triassic and a structural-geological analysis. The observations are then compared with the predictions of the different models.

2.1 Cold- vs. warm-water fauna

In the underthrust model, the Qiangtang Terrane formed one single block that drifted northwards from the Gondwana margin. Permian to Middle Triassic sediments are expected to reflect this northward drift by showing a trend from cold to warm water faunas. Contemporaneous sediments on the NQT and SQT should not show a significant difference in palaeo-latitude (Pullen and Kapp, 2014). In the overthrust model, the NQT and SQT were separated by an ocean of unknown width. Contemporaneous Permo-Traissic sediments would then be deposited on terranes with potentially significantly different latitude and cold-water fauna is to be expected in the SQT, but not in the NQT (e.g., Li et al., 1995).

2.2 Metamorphic grade

In the underthrust model, the mélange is formed between the Qiangtang Terrane continental crust and the subducting oceanic plate, which is thought to subduct southward at a shallow angle. This implies that all mélange rocks were once buried below the Qiangtang continental crust, down to a depth of at least 35 km (Kapp et al., 2003b). In the overthrust model, the mélange, including high-pressure rocks, derive from the Shuanghu suture in the north of the study area. This mélange may include high-pressure rocks, but not necessarily exclusively, such as Franciscan (e.g., Agard et al., 2009). The distribution of metamorphic grade in the allochtonous units is thus an important criterion to distinguish between the two models.

2.3 Structural position of the mélange

In the underthrust model, the mélange is exhumed by normal faulting that produced metamorphic core complex-like domes south of the JSS suture zone. This occurred due to roll-back of the subducting slab (Kapp et al., 2000, 2003b; Pullen et al., 2011) or later during Jurassic extension (Fu et al., 2010a). Continental crust should thus lie structurally above the mélange, separated by normal faults. The opposite is to be expected in the overthrust model, which envisages the mélange to be thrust over the SQT. Mélange should thus structurally overlie autochtonous crustal rocks, separated by thrusts (Zhao et al., 2014).

3 The basic stratigraphic and lithological frame in the Qiangtang Terrane

Here we review the Permian to Jurassic stratigraphy of the study area (Fig. 2a), including lithofacies, paleontology, and paleogeography, with particular attention to the Late Triassic unconformity. Stratigraphic age assignments were made by correlating lithostratigraphy with biostratigraphic sections within or near the study area.

SED
7, 329–367, 2015

3.1 Pre-collision stratigraphy and lithologies

Pre-Ordovician basement rocks crop out in the SQT in the Rongma area around the Gangtang Co granite and as a thrust sheet at Mount Mayigang Ri. These rocks are dominantly quartzites and phyllites, experienced greenschist-facies metamorphism and were deformed twice (Zhao et al., 2014). Detrital zircons show that the basement was pre-Ordovician in age and has a Gondwana affinity (Dong et al., 2011). It is unconformably overlain by slates of the Tashishan Formation, dated as Middle to Late Orodovician with Sinoceras-Michelinoceras fossils (Li et al., 2004; Zhao et al., 2014). Within the area, Ordovician rocks are only found in two small areas near Rongma Village. The Devonian is only represented in the NQT, where Carboniferous limestones are found just north-east of the study area (Li, 2006). Carboniferous sandstones with cephalopod fossils also unconformably overlie Pre-Ordovician basement rocks west of Rongma. Fossiliferous Carboniferous siltstones in the NQT were dated as Late Carboniferous (Wu et al., 2009). Ordovician to Carboniferous sediments are not metamorphosed and only one deformation phase can be recognized by folding, boudinage and cleavage development (Zhao et al., 2014). The first deformation phase observed in the basement is thus pre-Ordovician, whereas the second must be post-Carboniferous.

Only the Middle Permian Longge Group (P_2l) is found in the SQT. This unit comprises massive, poorly bedded reef or platform limestones including micritic bioclastic limestone, sparry oolitic limestone, dolomicrite, and brecciated dolomite. Fossils are abundant, including stromatoporoids, crinoids, brachiopods, gastropods, corals, benthic foraminifera and fusuline, constraining the age to the Middle Permian. This fusuline fauna is characterised by the presence of the distinctive bi-temperate fossils (Zhang et al., 2014). These strata occur as large fault-bounded rafts within the mélange, with a maximum thickness of ~ 5000 m. Early to Middle Permian strata are absent in the NQT, where only the Upper Permian Rejuechaca Group (P_3r) occurs. It consists of grey to light grey massive bioclastic limestone and dark-green layered micritic limestone with brachiopods and gastropods. These platform limestones reach >500 m in thickness

SED
7, 329–367, 2015

and contain marine faunas of typically Cathaysian provenance (Wu and Lang, 1990; Chen et al., 2009; Zhang et al., 2012b).

Late Permian to Middle Triassic strata are missing in the SQT. However, in the NQT, the Lower Triassic Kanglu Group (T_1k) conformably overlies the P_3r. Its thickness can reach ~ 950 m. This unit consists mainly of cyclically alternating purple, yellow or grey, fine-grained sandstones, siltstones and marls. The Lower Triassic age is confirmed by the presence of Claraia fossils. The overlying, > 1500 m thick Yingshuiquan Group (T_{1-2}y) consists of light grey massive oolithic limestone intercalated with thinly layered quartz and feldspathic sandstone. The limestones are sandy and contain abundant bivalves and brachiopods. The Lower Triassic sequence is topped by the Kangnan Group (T_2k) (< 310 m), which consists of grey-green fine-grained marls at the base and a bivalve rich limestone at the top.

3.2 Syn- to post collision stratigraphy and lithologies

The terrane-wide, Late Triassic unconformity marks the end of subduction activity (Zhai et al., 2011a) and the beginning of a new cycle of sedimentation that continued through most of the Mesozoic.

In the NQT, the base of the Late Triassic sequence is formed by T_3x, T_3j and T_3z. Polymictic conglomerates, pebbly siltstone and mudstone are found at the base of the Xiaoqiebao Group (T_3x). Overlying the basal conglomerate are pillow basalt, basaltic lavas, andesite, rhyolite, tuffites, intraformational breccias, and mass flow deposits. These, in turn, are overlain by several tens of meters coral-bearing limestones and plant debris-bearing sandstone with some conglomerate. The Jiaomuchaca Group (T_3j) overlies the Xiaoqiebao Group (T_3x). The lower part of the T_3j consists of conglomerates and platform-facies, limestone, while the upper part is formed by reefal limestone with coral, branchiopods, sponges and crinoids (Zhu et al., 2013). In the conglomerate, compositions of the gravels include poorly sorted volcanic debris, limestone and cherts. The upper most unit is Zhana Group (T_3z) that mainly consists of fine-grained lithic sandstone, tuffaceous sandstone, and siltstone (Zhang et al., 2005). The total thickness of these units is more than 2000 m.

The Late Triassic Nadigang Ri Group (T_3n) in the NQT starts with a set of fluvial conglomerates (Zhu et al., 2013), followed by mainly basaltic volcanic breccia, basalt and layered quartz andesite. Minor terrestrial intervals occur in the predominantly volcanic succession. A rhyolite in this sequence was dated at 208 Ma (Wang et al., 2007). Total thickness of the Nadigang Ri Group is about 800 m.

Sediments of the Late Triassic Tumengela Group (T_3t) and Wanghuling Group (T_3w) are found in the middle of the study area, unconformably overlying the mélange. The Tumengela Group is characterized by thick-bedded pebbly coarse lithic sandstone and fine-grained feldspar-quartz sandstone at base. The middle unit is occupied by a dark grey, rhythmic sequence of layered carbonaceous shale, silty shale or greyish-yellow calcareous silt. The uppermost part is composed of grey micrite and dark-grey calcareous mudstone (Zhu et al., 2013). The Wanghuling Group commences with a conglomerate with highly variable clasts that include limestone, basalt, sandstone and also high-pressure rocks. Upwards, the conglomerate grades into sandstone intercalated with siltstone, followed by ≥ 300 m of tuffaceous sand- and siltstone, rhyolite, and limestone intercalations. One rhyolite layer was dated as 214 ± 4 Ma and actinolite from the underlying units gave an Ar-Ar age of 219.7 ± 6.5 Ma (Li et al., 2007; J. Wang et al., 2008).

On the SQT, Late Triassic sedimentation commenced with conglomerates to sandstones (Li and Wen, 2007) unconformably overlying Permian sediments, as well as mélange. In the south of the area, the basal clastic sediments are overlain by medium- to thick-bedded clastic sediments and carbonates of the Riganpei Co Group (T_3r) (> 3000 m). This fossiliferous group mostly consists of grey micritic limestone and oolitic limestone, intercalated with breccia limestone and calcarenite and shell-clastic limestone, deposited in a marginal sea or carbonate platform (Zhu et al., 2013).

From south to north the Late Triassic shows a transition from shallow marine, carbonate-dominated sediments towards terrestrial fluvial sediments and an increasing

SED
7, 329–367, 2015

amount of bimodal volcanic deposits that dominate the sequence in the NQT (Fig. 2b). Onset of sedimentation progresses from ~ 220 Ma in the south to ~ 206 Ma in the north.

3.3 Post-collision stratigraphy and lithologies

The Early Jurassic Quemo Co Group (J_1q, ~ 1700 m thick) unconformably overlies the T_3n on the NQT. The base of this unit is characterized by coarse clastic rocks deposited in a river-delta environment. This unit grade upwards into several cycles of mud limestone, oolitic limestone, mudstone, argillaceous siltstone and sandstone, representing an overall transgression (Fu et al., 2010b). This is followed by the Middle Jurassic Xiali Group (J_2x) that shows a regressive sequence throughout the North Qiangtang basin. The lower part of this unit is composed of mudstone interbedded with sparry oolitic limestone, while the upper part consists of mudstone, micritic limestone and gypsum intercalations (Zhang et al., 2006c).

In the southern part of the area, < 1000 m thick Jurassic strata of the Sewa Group ($J_{1-2}s$) conformably overlie the Triassic (T_3r). The group consists of dark shales, siltstones, fine- to medium-grained sandstones with olistoliths, limestone lenses and quartzites. The whole sequence of sandy foreshore or shore facies sediments is possibly related to the earliest stages of basin subsidence in the southern Qiangtang realm during Early Jurassic extension (Duan et al., 2009; Schneider et al., 2003) and Meso-Tethys formation (Baxter et al., 2009).

Tertiary (possible even Late Cretaceous) to recent terrestrial sediments, mostly conglomerates, cover the area in scattered, usually fault-bounded basins (Kapp et al., 2005).

3.4 Lithologies and metamorphism of the mélange in the Qiangtang Terrane

The subduction mélange, only found on the SQT, is divided into three lithologies: (1) ophiolitic mélange (Zhai et al., 2007, 2010); (2) sedimentary mélange, consisting of deep water clastic sediments together with blocks and rafts of high-pressure rocks; and (3) Permian limestones (Zhang et al., 2012a; Fig. 1b).

The ophiolitic mélange consists of gabbro, diabase and basalt blocks and lenses, intercalated with deep-water siltstone, with minor chert, mudstone, sandstone and limestone. The mafic rocks have ocean-island or MORB affinities (Zhai et al., 2004, 2007) and range in age from the Ordovician to Triassic. Ordovician to Carboniferous gabbro ages were reported from rocks in the NW of the study area (Fig. 1b), which were interpreted as Palaeozoic ophiolitic segments (Zhai et al., 2009, 2010, 2013). Permian ophiolitic mélange was first documented by Zhai et al. (2007) in the Jiaomu Ri area. Northwest of Rongma village, mélange of gabbro blocks, pillow basalt and minor ultramafic blocks embedded in siltstone have Permian and Triassic ages (Zhang et al., 2012a; Li et al., 2009). Most of these mafic rocks preserved their original structures such as amygdules in basalt (Fig. 3a). The gabbros show no signs of strong deformation, nor of metamorphism, in thin section (Fig. 3b). That means that the ophiolitic mélange was never buried to significant depths.

The sedimentary mélange is mainly found south of Mayigang Ri, north and east of Jiaomu Ri, and in an EW to SW-NE trending belt in the southern part of the study area (Fig. 1b). Its composition is highly variable and includes sandstone, siltstone, mudstone, cherts, thin-bedded limestone and minor mafic blocks. Competent lithologies are embedded as lenses in a strongly foliated matrix (Fig. 3c). Various sedimentary structures are preserved, such as Bouma sequences, graded bedding, load casts (Fig. 3d) and flute marks. Sections of the stratigraphy are preserved, but disturbed by folds and faults (Fig. 3e). The sediments are not metamorphosed, as can be seen from a lack of recrystallisation in a fine-grained siltstone (Fig. 3f). Fossils show that occasional limestone blocks are of Permian age (Zhang et al., 2012a). Preservation of fossils and primary sedimentary microstructures show that the sedimentary mélange was not metamorphosed.

High-pressure rocks are found in association with the clastic sediments and Permian limestones of the sedimentary mélange. Main outcrops of high-pressure rocks are located in Jiaomu Ri and south of Gangtang Co (Fig. 1b). They consist of phengite-quartz schists, blueschists and eclogites (Kapp et al., 2003b; Liu et al., 2011; Zhai et al., 2011b; Zhang et al., 2006a). Peak metamorphic age is ~ 244 Ma and exhumation occurred around 220–214 Ma (Zhai et al., 2011b; Pullen et al., 2011). Maximum temperature and pressure ranges are 410–460 °C and 2.0–2.5 GPa. All authors agree that the exhumation was related to subduction, although the mechanism and plate tectonic setting remains under debate (Li et al., 2009; Pullen and Kapp, 2014; Kapp et al., 2003b; Zhang et al., 2006b).

At this stage it is useful to compare the stratigraphy described here with that of the detailed map of the Rongma and Jiaomu Ri area of Kapp et al. (2003). These authors define two types of mélange: blueschist (*bsch*) and greenschist facies (*gsch*) mélange. The *bsch*, which is readily identified in the field and on satellite images, corresponds to the high-pressure rocks described above. According to Kapp et al. (2003) *gsch* mélange only occurs west of the Jiangaizangbu valley in areas that we classified as ophiolitic or sedimentary mélange. Large areas that we mapped as mélange, because of the chaotic nature and strong deformation of the rocks, were assigned to an autochtonous Carboniferous (*C1-2*) to Permian (*P1-4*) series that overlies the mélange in the interpretation of Kapp et al. (2003). The Carboniferous sandstone, siltstone phyllite and slate (*C1*) west of Rongma are equivalent to the Pre-Ordovician basement and overlying Ordovician and Carboniferous metasediments (Zhao et al., 2014). *C1* northeast of Rongma is part of the sedimentary mélange. Fossil evidences show that the *C2* sandy limestone interbedded with siliciclastics actually belongs to the Middle Permian Longge Group (P_2l; Zhang et al., 2012a, 2014).

The Permian sequence of Kapp et al. (2003b) begins with turbiditic fine-grained volcaniclastic greywacke, sandstone, siltstone, and slate (*P1*) and thinly bedded dark-grey limestone (*P2*), both of which are part of the sedimentary mélange in our interpretation. Part of the basalts, and volcano-sedimentary sandstones to conglomerate/breccia (*P3*) corresponds to the Late Triassic Tumengela Group (T_3t) and Wanghuling Group (T_3w), the latter dated at 214 ± 4 (SHRIMP) to 206 ± 4 (Ar-Ar) Ma on rhyolite and basalt of the

Wanghuling Group (Li et al., 2007; Zhu et al., 2005). Other outcrops of *P3* we assigned to either ophiolitic mélange (dominated by mafic rocks) or the sedimentary mélange (dominated by sediments and breccias). The limestone and subordinate sandstone (*P4*) corresponds to the sediments of the top of the Wanghuling Group in areas where *P3* corresponds to its base. In the remainder of the area northeast of Jiaomu Ri, *P3* is mapped as sedimentary mélange.

As pointed out by Zhang (2012), the differences in stratigraphic and lithological classification clearly have major consequences for the inferred tectonic history of the Qiangtang area. In the map of Kapp et al. (2003b) the area of mélange is less than half that shown in Fig. 1. Furthermore, all mélange is at least greenschist facies, derived from depths of ≥ 35 km. Greenschist facies rocks can indeed be found in the ophiolitic and sedimentary mélange, but these occur together with non-metamorphic rocks. The whole mélange unit is therefore non-metamorphic, but includes metamorphic rocks from various origins, such as the Qiangtang basement (Zhao et al., 2014).

3.5 Igneous activity in the Qiangtang Terrane

Apart from the ophiolites, the Qiangtang area records Carboniferous to Jurassic igneous activity. EW striking diabase dykes intrude basement rocks and were dated at 284 ± 3 and 302 ± 4 Ma by Zhai et al. (2009). Mostly felsic magmatic activity is dated between about 275 and 248 Ma in the NQT east of the study area and interpreted as related to northward subduction underneath the NQT (Yang et al., 2011; Zhang et al., 2013). This is followed by bimodal activity that continued into the Jurassic (Zhang et al., 2011). Triassic (236–219 Ma) adakites and magnesian andesites from the Tuotuohe area, central NQT, are interpreted as subduction related, but indicate that the mantle source was metasomatized by slab melting (Q. Wang et al., 2008). Some basalts show continental arc affinities, the source most likely being a mixture of MORB- and Within Plate basalts-type source. This suggests the lithospheric mantle may be slightly to moderately enriched, most likely by a previous subduction process (Zhai et al., 2004).

SED
7, 329–367, 2015

Along the southern margin of the NQT the Nadigang Ri group is mainly composed of acid tuff, dacite, rhyolite and minor basaltic volcanic rocks ranging in age between 223 and 205 Ma (Zhai and Li, 2007; Fu et al., 2008). These rocks show a trend from melt generated by melting of subducted slab (ca. 223–219 Ma) to melting of Proterozoic oceanic crust (ca. 215–205 Ma; Zhai et al., 2012). Bimodal activity continued to ~ 177 Ma (Zhang et al., 2011) and includes the intrusion of the Gangtang Co granite at ~ 210 Ma (Kapp et al., 2003b; Hu et al., 2012). Granite samples from Gangtang Co granite (unpublished data) show a deep Eu anomaly as normalised to EMORB or OIB, and show REE contents similar to OIB-derived melts. Some trace element concentrations, such as Ta, Yb, Nb, Y, and Rb, suggest granite formation in a syn-collisional volcanic arc environment. The mafic lavas were probably derived from the mantle, whereas the felsic lavas were probably derived from partial melting of the continental crust in response to the asthenospheric upwelling (Zhang et al., 2011).

4 Structures and tectonics of the mélange in mapping area

Although there is abundant data on stratigraphy and igneous activity in the area, only few (and contradicting) structural analyses have been published so far (e.g., Kapp et al., 2003; Pullen et al., 2011; Liang et al., 2012; Zhao et al., 2014). Below we present the results of detailed mapping in conjunction with 3-D modelling using satellite images and the program 3D MoveTM by Midland Valley. The false-colour ASTER images proved to be very useful, as different units can be recognized clearly and mapped in non-accessible areas after ground-thruthing in mapped areas. The high topography also allows orienting the main structures and faults on the large scale.

The large-scale structure was modelled for three areas: SE of Mayigang Ri, NW of Rongma and NE of Jiaomu Ri (Fig. 4; see Fig. 1a for locations). The block diagrams show that the various units form a large-scale fold-and-thrust belt. Precambrian basement, exposed at Mayigang Ri, forms a flat-lying, N-dipping sheet that overlies a sheet of sedimentary mélange, separated by a ~ 5–20° NE-dipping fault gouge (Fig. 5a). The

SED
7, 329–367, 2015

upper few tens of metres of the underlying sedimentary mélange are strongly sheared with a top-to-the-south sense of shear. The sedimentary mélange is itself underlain by ophiolitic mélange. Lithologies and main foliations are approximately parallel and follow the contacts between the various units, interpreted as thrusts. All units and main foliation are folded with shallowly plunging, EW-striking fold axes (Fig. 4). To the south, north of Gangtang Co, the ophiololitic mélange is thrust over N-dipping Precambrian basement and slivers of Ordovician slate (Figs. 4, 5c). Unfortunately, most of this area is covered by Tertiary sediments.

West of Rongma, NE-dipping ophiololitic mélange overlies Precambrian basement and Ordivician and Carboniferous sediments (Fig. 5b). The main and only foliation in these latter units, as well as the second foliation (Sb2) in the underlying basement rocks also dip to the NE and increases in intensity towards the contact. The contact itself was initially a ductile shear zone that was overprinted by brittle deformation, as mylonitic rocks are found as clasts in brittle breccias. Sigmoidal clasts in Ordovician sediments indicate a top-to-the-south shearing (Fig. 3g). To the east, the ophiololitic mélange is overlain by a sheet of sedimentary mélange, followed by a sheet of blueschists that contain marble lenses. The blueschists are gently folded around NS-striking fold axes. The strongly deformed high-pressure rocks are overlain by a sheet of non-metamorphic and relatively undeformed Permian limestones. The sequence of ophiolitic mélange, sedimentary mélange and blueschists is repeated again towards Jiaomo Ri. The shallow-dipping blueschists clearly overlie the sedimentary mélange (Fig. 5d).

The large-scale structure of the area is thus a fold and thrust belt of, from bottom to top, Qiangtang basement (Precambrian to Carboniferous), ophiolitic mélange and finally juxtaposed sedimentary mélange, blueschists and rafts of Permian sediments. All these units have a dominant tectonic foliation that is approximately parallel to the main lithological boundaries. This foliation is the second foliation (Sb2) in the Precambrian basement (Fig. 3h), the first in the Carboniferous and Ordivician sediments (So1, Fig. 3g) and the main one (Sm1) in the mélanges, which wraps around lenses and

SED
7, 329–367, 2015

clasts. The parallelism of these foliations between the different units and with the main sheets indicates that they all formed during the thrusting event that created the stack of sheets. This is confirmed by So2 west of Rongma, which is approximately parallel to bedding, causing boundinage and locally south-vergent isoclinal folding (Fig. 3i). It increases in intensity towards the mylonitic/breccia contact with the overlying ophiolitic mélange, as is to be expected if So2 was formed during thrusting of that mélange over the basement.

The ~ 8 km thick stack of sheets is folded and thrusted on the > 10 km scale. The thickness of the stack, here derived from mapping and structural reconstructions, is confirmed by seismic data of Lu et al. (2013) and Li et al. (2013). The strike of the thrusts rotates from EW in the north towards NS in the east. In the southern part of the area folding and thrusting is south-vergent again (Fig. 4). This variation in trends is interpreted as the result of later doming of the Central Qiangtang Culmination, which may have occurred as late as the Jurassic (Kapp et al., 2003a). Late Triassic limestones and overlying basalts discordantly overlie the sedimentary mélange and blueschists. These Triassic units are almost undisturbed and undeformed and shallowly dip to the east. The absence of equivalent Late Triassic sediments further west may be because these were never deposited here, or because of the aforementioned doming, which the upper units now removed by erosion. The discordant contact between Late Triassic layers and underlying mélange and blueschists, as well as the lack of deformation in the Late Triassic layers is evidence that sheet-parallel thrusting happened before the ~ 210 Ma Triassic sedimentation. Further evidence is the fact that the undeformed 210 Ma Gangtang Co granite is in intrusive contact with basement rocks and ophiolitic mélange and clearly cuts the contact between these two units (Fig. 1b; Zhao et al., 2014). Formation of the sheet stack can thus be constrained to have occurred between about 220 Ma (Ar-Ar age of blueschists, Zhai et al., 2011a, b) and 210 Ma, being the age of the granite intrusion and onset of Late Triassic sedimentation.

Timing of the folding and thrusting of the sheet stack is less clear. Folding of Late Triassic and Jurassic units in the south of the area and even occasional folding of Tertiary

SED
7, 329–367, 2015

conglomerates are clear evidence for Mesozoic to Tertiary tectonic activity (Kapp et al., 2005). Late Triassic sedimentation commenced earlier in the south than in the north of the SQT terrane. This suggests the presence of a foreland basin or depression in front of the thrust belt (Fig. 5e), with sedimentation progressively extending to the north as erosion flattened the topography. It cannot be excluded that the fold and thrust belt, at least in part, occurred in the Late Triassic.

5 Discussion

5.1 Summary of main events and structures

Any model for the tectonic evolution of the Qiangtang terrane(s) must take the following observations into account:

1. The SQT is a continental terrane with Gondwana affinity (Dong et al., 2011; Zhao et al., 2014) that comprises a Precambrian basement that is unconformably overlain by Ordovician to Middle Permian sediments.

2. Subduction-related igneous activity in the NQT ranges in age from 275 to 248 Ma (Yang et al., 2011; Zhang et al., 2013) and is attributed to subduction of the Paleo-Tethys to the north at the Shuanghu suture (Yang et al., 2011), or alternatively to southward subduction of the Paleo-Tethys towards the south at the JSS suture (Q. Wang et al., 2008). Equivalent igneous activity is lacking in the SQT. Both the NQT and SQT saw bimodal igneous activity, ranging in age from 236 to 177 Ma, with signatures indicating mafic underplating and ensuing crustal melting (Zhang et al., 2011). Most authors attribute this to some form of slab break-off (Zhai and Li, 2007; Zhang et al., 2011; Peng et al., 2014).

3. Although all workers agree that high-pressure rocks and subduction-related mélange crop out in the centre of the Qiangtang terrane, there is no agreement

on the extent and classification of the various rocks. According to some authors, most of the area under consideration is a single "metamorphic belt" (e.g., Zhang et al., 2011), which ignores the fact that many rocks in this area are not metamorphic. Furthermore, metamorphism in the Precambrian rocks is pre-Ordovician (Zhao et al., 2014) and is unrelated to the Triassic high-pressure metamorphism of the blueschists. An opposite view is taken by Kapp et al. (2003), who restrict the mélange to greenschist- to blueschist-facies rocks and classify the other, non-metamorphic rocks as part of the overlying Qiangtang continental crust. However, in our view this restricts the definition of mélange in the area too much, as large areas are mélange, but not metamorphic. Based on our mapping, we define three main mélange lithologies: an ophiolitic and a sedimentary mélange, both not metamorphosed (but carrying metamorphic inclusions), and a high-pressure unit.

4. The ophiolitic mélange consists of a range of sediments and abundant gabbros and basalts. A coherent oceanic crust sequence is, however, not observed. Ages of the mafic rocks range from Ordovician to Triassic.

5. The high-pressure rocks experienced peak metamorphic conditions at ∼ 240 Ma and exhumed between 220 and 210 Ma, giving a minimum exhumation rate of > 1 cm yr^{-1} (Zhai et al., 2011b).

6. In the Rongma area, the main units form a stack of sheets with Precambrian to Carboniferous basement at the base, the ophiolitic mélange in the middle and sedimentary mélange with large rafts of blueschists and non-metamorphic Permian sediments towards the top.

7. Formation of the sheet stack by S to SW thrusting took place between about 220 and 210 Ma. It was postdated by intrusion of the undeformed, 210 Ma Gangtang Co granite and onset of Late Triassic sediment deposition and volcanic activity.

8. The sheet stack was folded and thrusted, again in an S to SW direction. Timing is uncertain and can range from the Late Triassic to the Mesozoic.

5.2 Existence of a Paleo-Tethys ocean and direction of subduction

The first question that needs to be addressed is whether North and South Qiangtang are individual terranes that were separated by an ocean or not. One argument for the presence of this ocean is that glacial deposits and cold-water fauna indicate that South Qiangtang terrane remained at high southern latitudes until the Middle Permian. However, only Upper Permian, warm-water sediments are found in North Qiangtang terrane. It is thus possible that the North and South Qiangtang terranes moved into warmer regions together between the Middle and Late Permian. As was discussed by Pullen et al. (2014), cold and warm-water faunas in the NQT and SQT neither prove, nor disprove a separation of the two terranes.

Permian to Triassic igneous activity in the North Qiangtang terrane is evidence for subduction underneath the North Qiangtang up to the Late Triassic. Because equivalent igneous activity is lacking in the SQT, most authors favour a northward subduction of the Shuanghu-Tethys underneath the NQT (Yang et al., 2011; Zhai et al., 2011a). However, Pullen and Kapp (2014) favour a southward subduction of the JSS-Tethys underneath a single Qiangtang Terrane. The main argument for this is that in their structural interpretation, the subduction mélange in the Qiangtang terrane lies underneath the continental crust, and was later exhumed by doming and normal faulting. The question is thus whether the mélange lies below or above continental crustal rocks. Several arguments are in favour of the latter. If the mélange was below the crust, it came from a depth of at least 35 km (Kapp et al., 2003) and all mélange rocks must be metamorphic. This is not the case. Even with the restrictive definition of mélange in the map of Kapp et al. (2003), areas mapped as greenschist are not all metamorphosed (Fig. 3a–e). As not all mélange rocks are metamorphic, they cannot all have come from a depth of tens of kilometres, as required in the underthrust model. Furthermore, this model requires a very shallow subduction angle for the subduction mélange to be at a relatively

SED
7, 329–367, 2015

shallow depth 200 km south of the suture. This cannot explain the subduction-related igneous activity only in the north, close to the postulated suture. Finally, our mapping and structural interpretation clearly favours emplacement of the mélange on top of the continental crust (Fig. 4).

5.3 Models for exhumation of high-pressure rocks in central Qiangtang Terrane

The presence of high-pressure rocks is one of the arguments to invoke subduction to the south or north of the NQT. The southward underthrust model of Kapp et al. (2000) provides a clear mechanism of exhumation of the high-pressure rocks: metamorphic core complex-like doming. Proponents of the northward subduction of a Shuanghu-Tethys underneath the NQT do not provide detailed mechanisms on the exhumation of the high-pressure rocks. Most authors propose high-pressure metamorphism at the downgoing slab, with subsequent exhumation in the orogenic wedge, possibly related to slab break-off (e.g., Zhang, 2006a; Li et al., 2009; Liu et al., 2011; Yang et al., 2011; Zhai et al., 2011a, b, 2012; Tang and Zhang, 2013). One problem with this exhumation in a convergent setting is that it should be related to extensive erosion during exhumation, which appears inconsistent with the regional sedimentary record (Pullen and Kapp, 2014).

5.4 Proposed tectonic evolution

Below we provide an overview of the sequence of tectonic events that affected the Qiangtang area. The model we propose aims to explain our observations made in the study area and those published in the literature. Of particular relevance are: (1) the NQT and SQT were separated by an ocean of unknown width; (2) the high-pressure rocks and tectonic mélange are found in a fold-and-thrust belt of a stack of three sheets: basement rocks, ophiolitic mélange and sedimentary mélange, together with HP rocks and undeformed Permian sediments; (3) mafic rocks in the ophiolitic mélange range in age from the Ordovician to the Triassic.

SED
7, 329–367, 2015

5.4.1 Pre-Ordovician (> 470 Ma)

The Pre-Ordovician clastic metasediments form the oldest and structurally lowest unit of the Qiangtang basement. These rocks experienced low-grade metamorphism and one stage of deformation, leading to folding and the formation of the first cleavage (S_{b1}). This event is tentatively attributed to the Bhimphedian Orogeny (Cawood, 2007), when the basement rocks still formed part of (assembling) Gondwana (Zhao et al., 2014).

5.4.2 Ordovician to Permian (470–270 Ma)

Opening of the Shuanghu-Tethys between the NQT and the SQT probably commenced in the (Late) Ordovician. The SQT formed the passive northern margin of Gondwana on which sediments were deposited at various stages from the Ordovician to the Permian. Exposures of the Sumdo eclogites in the Lhasa Terrane may indicate that the SQT and North Lhasa Terrane together separated from Gondwana as early as the Carboniferous (Yang et al., 2009). Initial rifting and subsequent ocean spreading produced mafic rocks with ages ranging from the Ordovician to the Permian in central Qiangtang (Zhai et al., 2010, 2012, 2013).

5.4.3 Upper Permian to Lower Triassic (270–240 Ma)

Northward subduction of the Paleo-Tethys underneath the NQT commenced at ~ 275 Ma, as is indicated by arc activity in the NQT (Yang et al., 2012; Fig. 6a). The youngest known passive margin sediments (P_2l) were deposited on the SQT, but no sedimentation occurred at the active southern margin of the NQT where arc volcanism occurred instead. Ocean-floor sediments and mafics from the oceanic crust were accreted to the NQT: the future ophiolitic mélange (Zhai et al., 2010, 2012, 2013). Although igneous activity indicates that most of the subduction occurred on the northern margin of the Shuanghu-Tethys, the southern margin, with cold, > 100 million years old

SED
7, 329–367, 2015
Tectonic evolution of the Qiangtang Terrane, Tibet
Z. Zhao et al.

oceanic crust, would probably also have started to subduct (Fig. 6b). This would have brought oceanic crust and material from lower crust of the overriding SQT plate down to > 100 km by ~ 240 Ma, which is the age of peak metamorphism in the high-pressure rocks (Pullen et al., 2011).

5.4.4 Middle Triassic (240–220 Ma)

With (minor) suduction to the south as well, the Shuanghu-Tethys plate would have formed a divergent double subduction zone (Gray and Foster, 2004; Soesoo et al., 1997; Zhao, 2014) with a long slab subducting to the north and a short one to the south. As a result, the NQT and SQT converged. At some point in this scenario, the slab pull of the long slab will override the opposite pull of the short slab, which results in the short one being pulled up and towards the north (Fig. 6c). This scenario was proposed for the Shuangu-Tethys by Liu et al. (2011) and is similar to the current situation of the Adria plate, which subducts underneath Italy (short slab) and the Dinarides (long slab; Giacomuzzi et al., 2012; Di Stefano et al., 2009; Gvirtzman and Nur, 2001). The Adria plate now moves as a whole towards the Dinarides, causing rapid extension east of the Apennines (Weber et al., 2010; Devoti et al., 2008). Extraction of the slab from underneath the SQT causes extension of its margin, while high-pressure rocks exhume. Trench and Permian margin sediments are dragged off the margin and brought in contact with the exhumed high-pressure rocks from below to form the observed association of sedimentary mélange, rafts of Permian sediments and blueschists. All these rocks, as well as the SQT Pre-Cambrian to Carboniferous basement are expected to experience strong flattening strain due to the extension, as well as a top to the south shearing. This is consistent with the D_2 deformation in basement rocks (S_{b2}, S_{o1}) and main foliation in the sedimentary mélange (S_{m1}). It should be noted that this core complex-like extension is to some extent similar to that proposed by Kapp et al. (2003) with the difference being that we propose the oceanic slab to form the core of the complex, not only the mélange. The structural relationships are in part similar as described by these authors: low-grade rocks juxtaposed onto high-pressure rocks in a strongly extensional setting.

A second effect of the extraction of the short slab is rising of the asthenosphere, with resulting mafic igneous activity, as well as melting of the crust, producing felsic melts. In the SQT bimodal activity is documented from ~ 236 Ma (Zhang et al., 2011).

5.4.5 Middle-Upper Triassic (220–200 Ma)

Northward movement of the Shuanghu-Tethys plate, during convergence of the NQT and SQT, carried the mix of sedimentary mélange and high-pressure rocks northward, towards and in the end on top of the accreted material at the northern suture, the ophiolitic mélange (Fig. 6d). As the two terranes collided, all these rocks were thrusted onto the SQT, producing the sheet stack as is now observed. At this stage, the Shuanghu-Tethys slab finally slid down into the mantle, giving rise to a last stage of astenosphere upwelling and resulting bimodal igneous activity, including the 210 Ma Gangtang Co granite and Upper Triassic rhyolites and basalts, mostly in the north, but extending south onto the (former) SQT (Fig. 6e). Postcollisional sediments, intercalated with volcanics, cover the amalgamated Qiangtang terrane. From south to north, these Upper Triassic deposits show two trends: from shallow marine, carbonate-dominated sediments towards terrestrial fluvial sediments and an increasing amount of bimodal volcanic deposits. This can be interpreted as a foreland basin that developed in the south in front of the thrust belt in the north. Southward propagation of thrusting finally thrusted mélange and P_2l in the hanging wall against latest Triassic sediments in the footwall (Fig. 5e).

5.4.6 Jurassic (200–170 Ma)

Following the closure of Longmu Co-Shuanghu suture zone, the Bangong-Nujiang suture zone opened between the amalgameted Qiangtang terrane and the North Lhasa terrane. Jurassic shallow marine deposits unconformably overlie Late Triassic T_3n sediments and volcanics on the NQT. Jurassic the deep-water flysch sediments ($J_{1-2}s$) sediments cover all the older units in the southern SQT. These are thought to represent the opening of the Bangong-Nujiang suture zone (Schneider et al., 2003; Baxter et al., 2009). It is not known whether Juarassic sediments once covered the whole Qiangtang terrane, or that they were never deposited here. Jurassic sediments, if once present, could have been removed during formation of the Central Qiangtang Culmination. This domal structure may have formed as early as the Jurassic (Kapp et al., 2005), or during compressional stages resulting from the closure of the Meso- and Neo-Tethys during the Cretaceous and Paleogene, respectively (Kapp et al., 2005; Xu et al., 2014). Minor terrestrial sediments, mostly conglomerates in fault-bounded basins, were deposited during the Cretaceous and Tertiary.

6 Conclusions

Subduction mélange and high-pressure rocks in the Qiangtang Terrane record an important stage in the evolution and formation of the Tibetan Plateau. Various definitions of the Central Qiangtang Metamorphic Belt, stratigraphic assignment of its rock units and different structural interpretations have led to a range of conflicting models on the formation of the belt, which has consequences for the location of different former oceans and the location and direction of their subduction. Mapping and structural analysis of the Rongma area in the centre of the metamorphic belt presented here sheds new light on the tectonic history and, in particular, favours the former presence of an Ordivician-Triassic ocean between the North and South Qiangtang terranes, which subducted mainly to the north (Li et al., 2009; Zhai et al., 2011a, b).

Metamorphism in the Central Qiangtang Metamorphic Belt occurred in two unrelated stages. The first occurred in Pre-/Early-Ordovician times and affected the Precambrian basement. Lower greenschist facies metamorphism and a first deformation phase record this event. A second event produced the high-pressure rocks that are found in the area. HP metamorphism and exhumation occurred in the Triassic as a

SED
7, 329–367, 2015

result of the closure at the Longmu Co-Shuang Hu suture zone between the North and South Qiantang terranes.

The pre- to syn-collision lithologies (> 210 Ma) can be grouped into three main units: (1) Carboniferous and older basement, (2) non-metamorphic ophiolitic mélange, and (3) non-metamorphic sedimentary mélange with large rafts and sheets of non-metamorphic Permian sediments and high-pressure rocks (mostly blueschists). To explain the current structural relationships of the units, we propose that the high-pressure rocks were exhumed by extraction of a short south-dipping slab from underneath the South Qiangtang terrane, bringing them in contact with the sedimentary mélange and Permian margin sediments. This unit was subsequently thrusted on top of the ophiolitic mélange. Upon final collision of the North and South Qiangtang terranes, both units were placed on top of the Paleozoic South Qiangtang basement. The whole tripartite stack was subsequently further shortened into a south-verging fold and thrust belt. This may have been a consequence of the amalgamation of the two terranes, or later (Jurassic–Paleogene) events.

After closure of the Longmu Co-Shuanghu suture zone, Upper Triassic sedimentation commenced in the south in a foreland setting and progressively extended to the north where extensive bimodal volcanic activity occurred, which is interpreted as the result of mantle upwelling due to the final sinking of the paleo-Tethys slab. Sedimentation continued into the Jurassic, especially in the south on the margin of the opening Bangong–Nujiang Suture Zone.

This study is based on a large study area in the centre of the Qiangtang terrane, which, however, extends over almost 2000 km. We hope that this study encourages more work, including detailed mapping and structural analysis, in the whole terrane to confirm or reject the former presence of an ocean between the North and South Qiangtang terranes, as well as investigate the consequences in terms of presence and size of other oceans between the various terranes that form the Tibetan Plateau.

Author contributions. Fieldwork was carried out by G. Wang and his team, including Y. Liu and Z. Zhao. Structural interpretations, modelling and thin section analyses were carried out by

SED
7, 329–367, 2015

Z. Zhao and P. D. Bons. A. Soesoo scrutinized the geochemical data. The paper was written by all authors.

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References

Agard, P., Yamato, P., Jolivet, L., and Burov, E.: Exhumation of oceanic blueschists and eclogites in subduction zones: timing and mechanisms, Earth-Sci. Rev., 92, 53–79, 2009.

Baxter, A. T., Aitchison, J. C., and Zyabrev, S. V.: Radiolarian age constraints on Mesotethyan ocean evolution, and their implications for development of the Bangong-Nujiang suture, Tibet, J. Geol. Soc. London, 166, 689–694, 2009.

Chen, S., Cheng, L., Wu, S., and Zhu, Y.: Late Permian fusulinds from the Raggyorcaka Formation, northern Qiangtang, Tibet, China, Geological Bulletin of China, 28, 1725–1729, 2009.

Devoti, R., Riguzzi, F., Cuffaro, M., and Doglioni, C.: New GPS constraints on the kinematics of the Apennines subduction, Earth Planet. Sc. Lett., 273, 163–174, 2008.

Dewey, J. F., Shackleton, R. M., Chengfa, C., and Yiyin, S.: The tectonic evolution of the Tibetan Plateau, Philos. T. R. Soc. A, 327, 379–413, 1988.

Di Stefano, R., Kissling, E., Chiarabba, C., Amato, A., and Giardini, D.: Shallow subduction beneath Italy: Three-dimensional images of the Adriatic-European-Tyrrhenian lithosphere system based on high-quality P wave arrival times, J. Geophys. Res.-Sol. Ea., 114, 1978–2012, 2009.

Dong, C., Li, C., Wan, Y., Wang, W., Wu, Y., Xie, H., and Liu, D.: Detrital zircon age model of Ordovician Wenquan quartzite south of Lungmuco-Shuanghu Suture in the Qiangtang area, Tibet: Constraint on tectonic affinity and source regions, Sci. China Ser. D, 54, 1034–1042, 2011.

Duan, Z., Zhong, C., Zhu, H., Cheng, J., Li, Z., and Wang, Z.: Sedimentary characteristics of Middle Jurassic Sewa and Buqu Formations from Qiangzi Well-2, southern Qiangtang basin, Tibet, Geology in China, 36, 355–365, 2009.

Fu, X., Wang, J., Wang, Z., and Chen, W.: U-Pb Zircon Age and Geochemical Characteristics of Volcanic Rocks from the Juhua Mountain Area in the northern Qiangtang Basin , northern Xizang (Tibet), Geological Review, 54, 232–242, 2008.

Fu, X., Wang, J., Tan, F., Chen, M., and Chen, W.: The Late Triassic rift-related volcanic rocks from eastern Qiangtang, northern Tibet (China): Age and tectonic implications, Gondwana Res., 17, 135–144, 2010a.

Fu, X., Wang, J., Wu, T., and He, J.: Stratigraphy and paleoenvironment of the Quemo Co Formation in Shengli River area, northern Tibet, Geology in China, 37, 1305–1312, 2010b.

Giacomuzzi, G., Civalleri, M., De Gori, P., and Chiarabba, C.: A 3D Vs model of the upper mantle beneath Italy: Insight on the geodynamics of central Mediterranean, Earth Planet. Sc. Lett., 335, 105–120, 2012.

Gray, D. and Foster, D.: Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives, Aust. J. Earth Sci., 51, 773–817, 2004.

Gvirtzman, Z. and Nur, A.: Residual topography, lithospheric structure and sunken slabs in the central Mediterranean, Earth Planet. Sc. Lett., 187, 117–130, 2001.

Hu, P., Li, C., Su, L., and Zhang, H.: Geochemical and 40Ar-39Ar isotope chronological characteristics of Wugongshan Indo-Chinese granites in central Qiangtang, Tibetan Plateau, Geological Bulletin of China, 31, 843–851, 2012.

Kapp, P., Yin, A., Manning, C. E., Murphy, M., Harrison, T. M., Spurlin, M., Lin, D., Xi-Guang, D., and Cun-Ming, W.: Blueschist-bearing metamorphic core complexes in the Qiangtang block reveal deep crustal structure of northern Tibet, Geology, 28, 19–23, 2000.

Kapp, P., Murphy, M. A., Yin, A., Harrison, T. M., Ding, L., and Guo, J.: Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet, Tectonics, 22, TC1029, 1–24, doi:10.1029/2001TC001332, 2003a.

Kapp, P., Yin, A., Manning, C. E., Harrison, T. M., Taylor, M. H., and Ding, L.: Tectonic evolution of the early Mesozoic blueschist-bearing Qiangtang metamorphic belt, central Tibet, Tectonics, 22, 1043–1068, 2003b.

Kapp, P., Yin, A., Harrison, T. M., and Ding, L.: Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet, Bull. Geol. Soc. Am., 117, 865–878, 2005.

SED
7, 329–367, 2015

Tectonic evolution of the Qiangtang Terrane, Tibet

Z. Zhao et al.

Kapp, P., DeCelles, P. G., Gehrels, G. E., Heizler, M., and Ding, L.: Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area of central Tibet, Bull. Geol. Soc. Am., 119, 917–932, 2007.

Li, C.: The Longmu Co-Shuanghu-Lancangjiang Suture as the northern boundary of the Gandwanaland in the Carboniferous and Permian, Bull. Changcun Coll. Geol. Sci 17, 155–166, 1987.

Li, C.: Geological map of the Myyi Gang Ri area (Scale at 1:250,000), University of Jilin Region Institute of geological survey, China, 2006.

Li, C., Cheng, L., Hu, K., Yang, Z., and Hong, Y.: Study on the paleo-Tethys suture zone of Lungmu Co-Shuanghu, Tibet, Geol. Publ. House, Beijing, 1995.

Li, C., Cheng, L., Zhang, Y., and Zhai, Q.: Discovery of Ordovician-Devonian strat in the south of the Qiangtang area, Tibet, Geological Bulletin of China, 23, 602–604, 2004.

Li, C., Zhai, Q., Dong, Y., and Huang, X.: Discovery of eclogite and its geological significance in Qiangtang area, central Tibet, Chinese Sci. Bull., 51, 1095–1100, 2006.

Li, C., Zhai, Q., Dong, Y., Zeng, Q., and Huang, X.: Longmu Co-Shuanghu plate suture and evolution records of paleo-Tethyan oceanic in Qiangtang area, Qinghai-Tibet plateau, Frontiers of Earth Science in China, 1, 257–264, 2007.

Li, C., Zhai, Q., Dong, Y., Liu, S., Xie, C., and Wu, Y.: High-pressure eclogite-blueschist metamorphic belt and closure of paleo-Tethys Ocean in Central Qiangtang, Qinghai-Tibet plateau, J. Earth Sci., 20, 209–218, 2009.

Li, Q., Gao, R., Feng, X., Lu, Z., Hou, H., Ye, G., Li, P., Wang, H., Ye, Z., and Xiong, X.: Structural Characteristics of the Basement beneath Qiangtang Basin in Qinghai-Tibet Plateau: Results of Interaction Interpretation from Seismic Reflection/Refraction Data, Acta Geol. Sin.-Engl., 87, 358–377, 2013.

Li, X. and Wen, F.: Discovery of the Late Triassic Rigain Pünco Formation and the unconformity between it and its under lying strata in eastern Rutog, Tibet, China, Geological Bulletin of China, 26, 1009–1013, 2007.

Liang, X., Wang, G., Yuan, G., and Liu, Y.: Structural sequence and geochronology of the Qomo Ri accretionary complex, Central Qiangtang, Tibet: Implications for the Late Triassic subduction of the Paleo-Tethys Ocean, Gondwana Res., 22, 470–481, 2012.

Liu, Y., Santosh, M., Zhao, Z. B., Niu, W. C., and Wang, G. H.: Evidence for palaeo-Tethyan oceanic subduction within central Qiangtang, northern Tibet, Lithos, 127, 39–53, 2011.

Lu, Z., Gao, R., Li, Y., Xue, A., Li, Q., Wang, H., Kuang, C., and Xiong, X.: The upper crustal structure of the Qiangtang Basin revealed by seismic reflection data, Tectonophysics, 606, 171–177, 2013.

Metcalfe, I.: Late Palaeozoic and Mesozoic tectonic and palaeogeographical evolution of SE Asia, Geol. Soc. SP, London, 315, 7–23, 2009.

Nie, S., Yin, A., Rowley, D. B., and Jin, Y.: Exhumation of the Dabie Shan ultra-high-pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China, Geology, 22, 999–1002, 1994.

Peng, T., Zhao, G., Fan, W., Peng, B., and Mao, Y.: Late Triassic granitic magmatism in the Eastern Qiangtang, Eastern Tibetan Plateau: Geochronology, petrogenesis and implications for the tectonic evolution of the Paleo-Tethys, Gondwana Res., doi:10.1016/j.gr.2014.01.009, in press, 2014.

Pullen, A. and Kapp, P.: Mesozoic tectonic history and lithospheric structure of the Qiangtang terrane: Insights from the Qiangtang metamorphic belt, central Tibet, Geol. S. Am. S., 507, 507–504, 2014.

Pullen, A., Kapp, P., Gehrels, G. E., Vervoort, J. D., and Ding, L.: Triassic continental subduction in central Tibet and Mediterranean-style closure of the Paleo-Tethys Ocean, Geology, 36, 351–354, 2008.

Pullen, A., Kapp, P., Gehrels, G. E., Ding, L., and Zhang, Q.: Metamorphic rocks in central Tibet: Lateral variations and implications for crustal structure, Bull. Geol. Soc. Am., 123, 585–600, 2011.

Schneider, W., Mattern, F., Wang, P. J., and Li, C.: Tectonic and sedimentary basin evolution of the eastern Bangong-Nujiang zone (Tibet): A Reading cycle, Int. J. Earth Sci., 92, 228–254, 2003.

Soesoo, A., Bons, P. D., Gray, D. R., and Foster, D. A.: Divergent double subduction: tectonic and petrologic consequences, Geology, 25, 755–758, 1997.

Tang, X. and Zhang, K.: Lawsonite-and glaucophane-bearing blueschists from NW Qiangtang, northern Tibet, China: mineralogy, geochemistry, geochronology, and tectonic implications, Int. Geol. Rev., 1–17, 2013.

Wang, J., Fu, X., Chen, W., and Wang, Z.: The Late Triassic Paleo-weathering Crust in the Qiangtang Basin Northern Tibet: geology, geochemistry and significance, Acta Geol. Sin.-Engl., 25, 487–494, 2007.

Wang, J., Fu, X. G., Chen, W. X., Wang, Z. J., Tan, F. W., Chen, M., and Zhuo, J. W.: Chronology and geochemistry of the volcanic rocks in Woruo Mountain region, northern Qiangtang depression: Implications to the Late Triassic volcanic-sedimentary events, Sci. China Ser. D, 51, 194–205, 2008.
Wang, Q., Wyman, D. A., Xu, J., Wan, Y., Li, C., Zi, F., Jiang, Z., Qiu, H., Chu, Z., and Zhao, Z.: Triassic Nb-enriched basalts, magnesian andesites, and adakites of the Qiangtang terrane (Central Tibet): evidence for metasomatism by slab-derived melts in the mantle wedge, Contrib. Mineral. Petr., 155, 473–490, 2008.
Wang, S., Li, Z., and Qiangba, X.: Geologic map and geologic report of the Xigaze area, Tibetan Bur. of Geol. and Miner. Resour., Llasa, 1983.
Weber, J., Vrabec, M., Pavlovčič-Prešeren, P., Dixon, T., Jiang, Y., and Stopar, B.: GPS-derived motion of the Adriatic microplate from Istria Peninsula and Po Plain sites, and geodynamic implications, Tectonophysics, 483, 214–222, 2010.
Wu, G., Yao, J., and Ji, Z.: The Late Carboniferous Fusulinids in the central part of northern Qiangtang, Tibet,China, Geological Bulletin of China, 28, 1276–1280, 2009.
Wu, R. and Lang, B.: The new strata data of the Late Permian in northwest Tibet, Journal of stratigraphy, 14, 216–221, 1990.
Yang, J., Xu, Z., Li, Z., Xu, X., Li, T., Ren, Y., Li, H., Chen, S., and Robinson, P. T.: Discovery of an eclogite belt in the Lhasa block, Tibet: A new border for Paleo-Tethys?, J. Asian Earth Sci., 34, 76–89, 2009.
Yang, T., Zhang, H., Liu, Y., Wang, Z., Song, Y., Yang, Z., Tian, S., Xie, H., and Hou, K.: Permo-Triassic arc magmatism in central Tibet: Evidence from zircon U–Pb geochronology, Hf isotopes, rare earth elements, and bulk geochemistry, Chem. Geol., 284, 270–282, 2011.
Yin, A. and Harrison, T. M.: Geologic evolution of the Himalayan-Tibetan orogen, Annu. Rev. Earth Pl. Sc., 28, 211–280, 2000.
Yin, A. and Nie, S.: A Phanerozoic palinspastic reconstruction of China and its neighboring regions, World and Regional Geology, 442–485, 1996.
Zhai, Q. and Li, C.: Zircon SHRIMP dating of volcanic rock from Nadigangri Formation in Juhuashan, Qiangtang, Northern Tibet and its geological significance, Acta Geol. Sin.-Engl., 81, 795–800, 2007.
Zhai, Q., Li, C., and Huang, X.: The fragment of Paleo-Tethys ophiolite from central Qiangtang, Tibet: Geochemical evidence of metabasites in Guoganjianian, Sci. China Ser. D, 50, 1302–1309, 2007.

SED
7, 329–367, 2015

Zhai, Q., Li, C., Wang, J., Ji, Z., and Wang, Y.: SHRIMP U-Pb dating and Hf isotopic analyses of zircons from the mafic dyke swarms in central Qiangtang area, Northern Tibet, Chinese Sci. Bull., 54, 2279–2285, 2009.
Zhai, Q., Wang, J., Li, C., and Su, L.: SHRIMP U-Pb dating and Hf isotopic analyses of Middle Ordovician meta-cumulate gabbro in central Qiangtang, northern Tibetan Plateau, Sci. China Ser. D, 53, 657–664, 2010.
Zhai, Q., Jahn, B. M., Zhang, R., Wang, J., and Su, L.: Triassic Subduction of the Paleo-Tethys in northern Tibet, China: evidence from the geochemical and isotopic characteristics of eclogites and blueschists of the Qiangtang Block, J. Asian Earth Sci., 42, 1356–1370, 2011a.
Zhai, Q., Zhang, R., Jahn, B. M., Li, C., Song, S., and Wang, J.: Triassic eclogites from central Qiangtang, northern Tibet, China: Petrology, geochronology and metamorphic PT path, Lithos, 125, 173–189, 2011b.
Zhai, Q., Jahn, B., Su, L., Wang, J., Mo, X. X., Lee, H., Wang, K., and Tang, S.: Triassic arc magmatism in the Qiangtang area, northern Tibet: Zircon U-Pb ages, geochemical and Sr-Nd-Hf isotopic characteristics, and tectonic implications, J. Asian Earth Sci., 63, 162–178, 2012.
Zhai, Q., Jahn, B., Wang, J., Su, L., Mo, X., Wang, K., Suohan, T., and Lee, H.: The Carboniferous ophiolite in the middle of the Qiangtang terrane, Northern Tibet: SHRIMP U-Pb dating, geochemical and Sr-Nd-Hf isotopic characteristics, Lithos, 168, 186–199, 2013.
Zhai, Q. G., Li, C., Cheng, L., and Zhang, Y.: Geological features of Permian ophiolite in the Jiaomuri area, Qiangtang, Tibet, and its tectonic significance, Regional Geology of China, 23, 1228–1229, 2004.
Zhang, H., Yang, T., Hou, Z., Song, Y., Ding, Y., and Cheng, X.: Petrogenesis and tectonics of late Permian felsic volcanic rocks, eastern Qiangtang block, north-central Tibet: Sr and Nd isotopic evidence, Int. Geol. Rev., 1–12, 2013.
Zhang, K. and Tang, X.: Eclogites in the interior of the Tibetan Plateau and their geodynamic implications, Chinese Sci. Bull., 54, 2556–2567, 2009.
Zhang, K., Cai, J., Zhang, Y., and Zhao, T.: Eclogites from central Qiangtang, northern Tibet (China) and tectonic implications, Earth Planet. Sc. Lett., 245, 722–729, 2006a.
Zhang, K., Zhang, Y., Li, B., Zhu, Y., and Wei, R.: The blueschist-bearing Qiangtang metamorphic belt (northern Tibet, China) as an in situ suture zone: Evidence from geochemical comparison with the Jinsa suture, Geology, 34, 493–497, 2006b.

Zhang, K., Zhang, Y., Xia, B., and He, Y.: Temporal variations of Mesozoic sandstone compositions in the Qiangtang block, northern Tibet (China): implications for provenance and tectonic setting, J. Sediment. Res., 76, 1035–1048, 2006c.
Zhang, K., Tang, X., Wang, Y., and Zhang, Y.: Geochronology, geochemistry, and Nd isotopes of early Mesozoic bimodal volcanism in northern Tibet, western China: Constraints on the exhumation of the central Qiangtang metamorphic belt, Lithos, 121, 167–175, 2011.
Zhang, K. J.: Blueschist-bearing metamorphic core complexes in the Qiangtang block reveal deep crustal structure of northern Tibet: Comment, Geology, 29, 90, 2001.
Zhang, S., Wang, H., Feng, D., Jiang, X., Li, X., and Li, Q.: The Xiaochaka Group and Riganpeicuo Group stratigraphic sequence and correlation in the Qiangtang area, Tibet - question the validity of the boundary between Qiangnan and Qiangbei strata, Jilin Geology, 24, 16–20, 2005.
Zhang, Y., Shen, S., Shi, G., Wang, Y., and Yuan, D.: Tectonic evolution of the Qiangtang Block, northern Tibet during Late Cisuralian (Late Early Permian): Evidence from fusuline fossil records, Palaeogeogr. Palaeocl., 350, 139–148, 2012a.
Zhang, Y., Shi, G., and Shen, S.: A review of Permian stratigraphy, palaeobiogeography and palaeogeography of the Qinghai-Tibet Plateau, Gondwana Res., 24, 55–76, 2012b.
Zhang, Y., Shi, G., Shen, S., and Yuan, D.: Permian Fusuline Fauna from the Lower Part of the Lugu Formation in the Central Qiangtang Block and its Geological Implications, Acta Geol. Sin.-Engl., 88, 365–379, 2014.
Zhao, G.: Jiangnan Orogen in South China: Developing from divergent double subduction, Gondwana Res., doi:10.1016/j.gr.2014.09.004, in press, 2014.
Zhao, Z., Bons, P. D., Wang, G., Liu, Y., and Zheng, Y.: Origin and pre-Cenozoic evolution of the south Qiangtang basement, Central Tibet, Tectonophysics, 623, 52–66, 2014.
Zhu, D., Zhao, Z., Niu, Y., Dilek, Y., Hou, Z., and Mo, X.: The origin and pre-Cenozoic evolution of the Tibetan Plateau, Gondwana Res., 23, 1429–1454, 2012.
Zhu, T.: Geological map of the Jiangaida Ri area (Scale at 1:250,000): geology and resource institute of Chengdu, China, 2005.
Zhu, T., Feng, X., Wang, X., and Zhou, M.: Reconstruction of the Triassic Tectonic Lithofacies Paleogeography in Qiangtang Region, Northern Qinghai, Tibet Plateau, China, Acta Geol. Sin.-Engl., 87, 378–394, 2013.

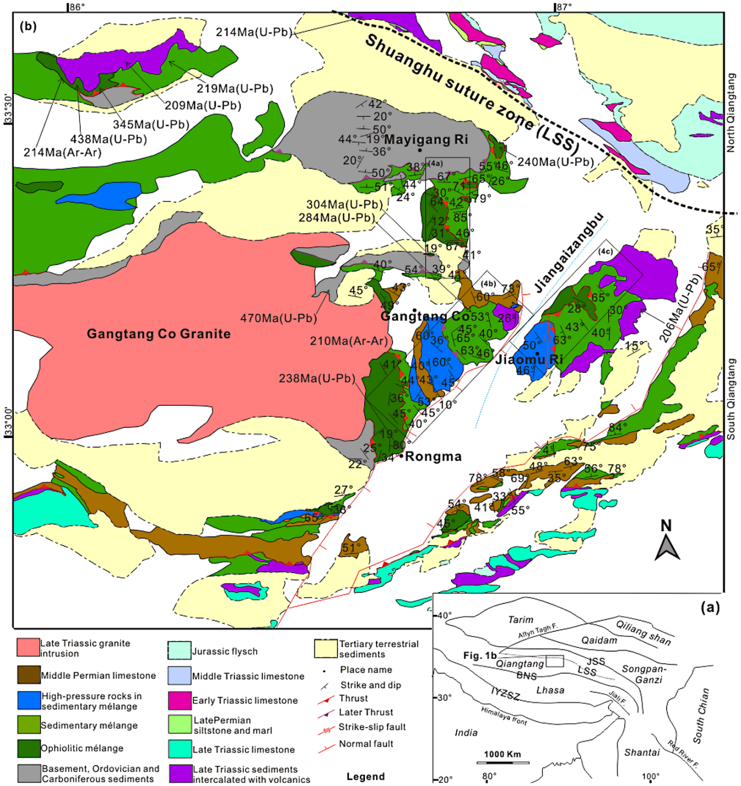

Figure 1. **(a)** Structural sketch of Tibet. From north to south, the sutures are JSS – Jinsha Suture Zone; LSS – Longmu Co-Shuanghu Suture Zone; BNS – Bangong-Nujiang Suture Zone; and IYSZ – Indus-Yarlung Suture Zone. **(b)** Geological map of the study area (rectangle in **(a)**) around Rongma on the northern margin of the South Qinagtang terrane. The LSS zone sparates the south Qiangtang from the North Qiangtang terrane in the northeast of the area. Strikes and dips are of the main tectonic foliation on strongly deformed rocks or bedding in less deformed rocks. Rectangles show the locations of structural reconstructions in Fig. 4.

SED
7, 329–367, 2015

Tectonic evolution of the Qiangtang Terrane, Tibet

Z. Zhao et al.

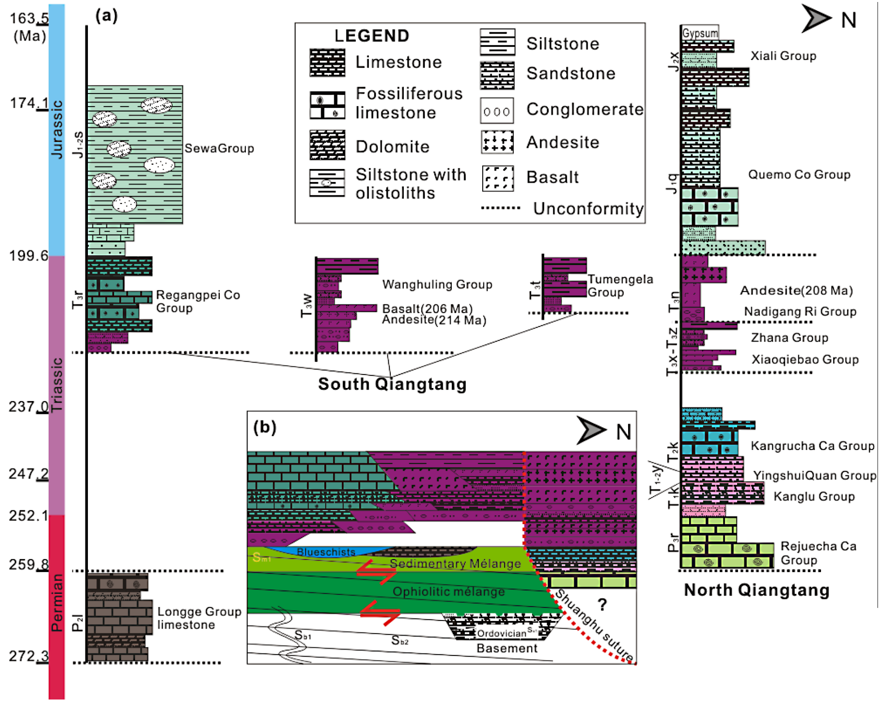

Figure 2. (a) Permian to Jurassic lithostratigraphic columns for the Qiangtang area, from south (left) to north (right). **(b)** Structural and stratigraphic relationships. Basement, ophiolitic mélange and sedimentary mélange with blueschists and Permian sediments form a stack of thrust bounded sheets. These are unconformably overlain by Late Triassic sediments and volcanics.

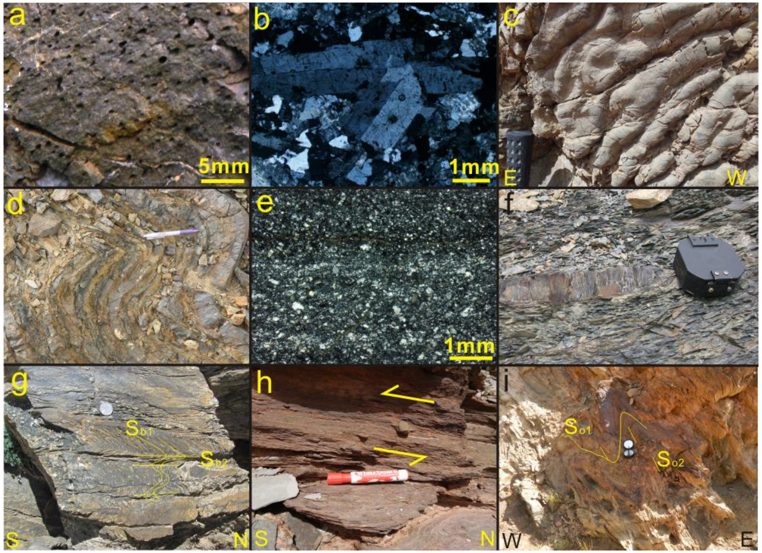

Figure 3. Field photographs and micrographs showing metamorphism and deformation in the different units. **(a)** Amygdules in basalt from the ophiolitic mélange, west of Rongma. **(b)** Thin sections of gabbro, west of Rongma. **(c)** Load cast in mudstone from southern part of the sedimentary mélange. **(d)** Folds of cherts from sedimentary mélange west of Jiangaizangbu River. **(e)** Thin sections of siltstone, west of Rongma. These structures show that the ophiolitic and sedimentary mélanges did not experience any significant metamorphism. **(f)** Typical main foliation in the sedimentary mélange wrapping competent blocks, here sandstone. **(g)** Outcrop view of basement deformation. S_{b1} is folded during which a second, crenulation cleavage S_{b2} developed. **(h)** Pressure shadow around pebbles in the Ordovician siltstone indicate top-to-south shearing. **(i)** Near the thrust where ophiolitic mélange is thrusted over Ordovician sediments (Fig. 5b), the sediments are deformation is more intense, with the local development of an axial planar So_2.

SED
7, 329–367, 2015

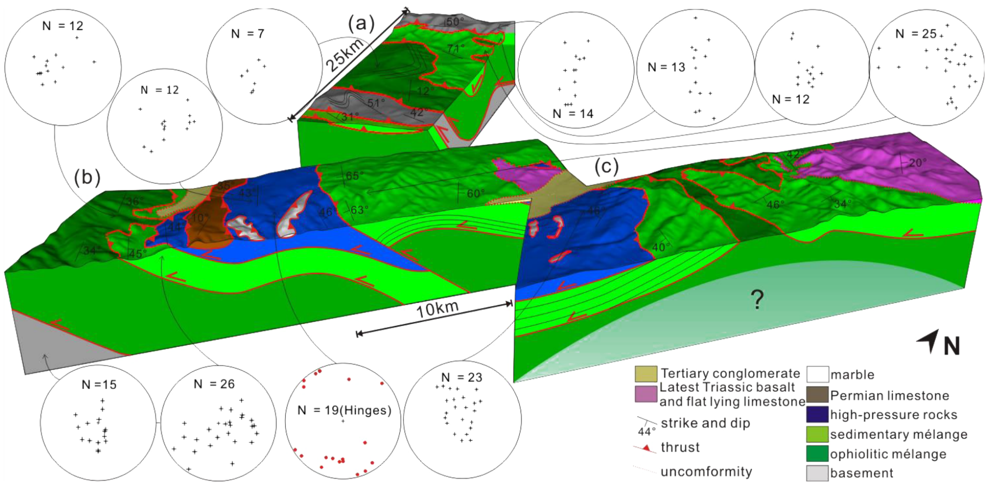

Figure 4. 3-D reconstruction of selected areas near Rongma in the centre of the area showing the fold-and-thrust geometry of three main sheets: basement, ophiolitic mélange and sedimentary mélange together with high-pressure rocks and rafts of (Permian) sediments. These are unconformably overlain by Late Triassic sediments. **(a)** South of Mayignag Ri, **(b)** northeast of Rongma and **(c)** northeast of Jiaomu Ri (see Fig. 1b). Lower-hemisphere equal-area stereoplots show the distribution of the main foliations (black crosses), as well as orientations of fold axes (red dots).

SED
7, 329–367, 2015

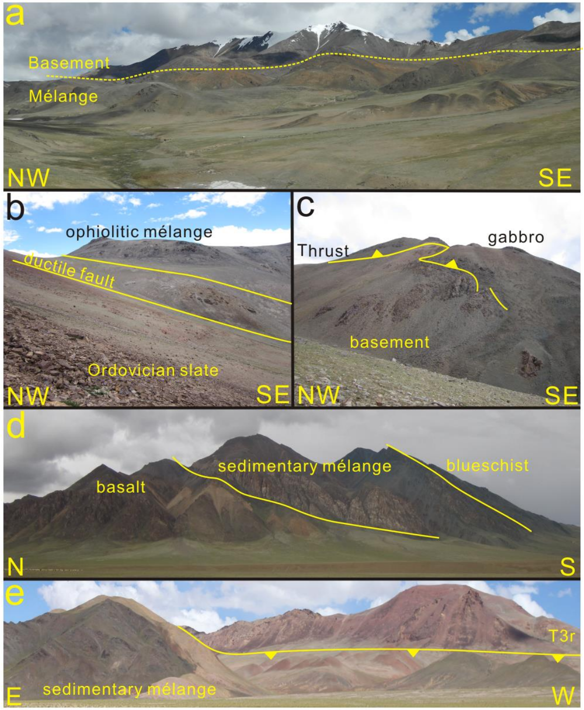

Figure 5. Field relationships of the main units. **(a)** View to the NW towards the Mayigang Ri Thrust, which thrusted basement on top of sedimentary mélange thrust which rest the basement onto the mélange. **(b)** West of Rongma, ophiolitic mélange is thrusted on top of basement and Ordovician sediments, now separated by a wide fault zone. **(c)** Folded thrust that paced gabbros of the ophiolitic mélange on top the basement, north of Gangtang Co. **(d)** View from the north towards Jiaomu Ri, clearly showing that blueschist lies above the sedimentary mélange, which in turn overlies basalts of the ophiolitic mélange. **(e)** North-dipping thrust places subduction mélange over Late Triassic limestone (T_3r) in the south of the study area, showing that at least part of the thrusting postdated the Late Triassic.

SED
7, 329–367, 2015

Tectonic evolution of the Qiangtang Terrane, Tibet

Z. Zhao et al.

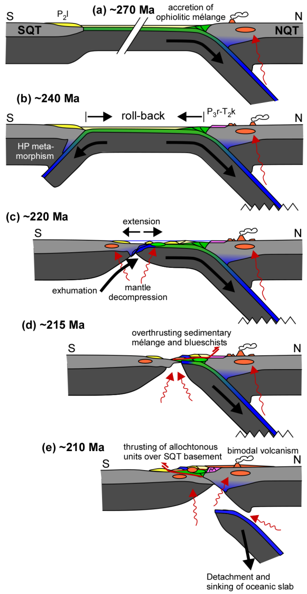

Figure 6. Schematic drawings of the Permian to Early Jurassic geological evolution of Shuanghu-Tethys. Ages shown in the drawings are approximate only. **(a)** Northward subduction of the Shuanghu-Tethys underneath the NQT started at about 275 Ma. **(b)** Minor southward subduction would have commenced in the Early Triassic, necessitating rollback and convergence of the NQT and SQT. **(c)** Interaction between the converging subduction zones led to extraction of the short southern slab and concomitant exhumation of high-pressure rocks. These are brought in contact with surface derived margin sediments and basement in a strongly extensional setting. **(d)** With ongoing convergence of the NQT and SQT, the sedimentary mélange (with high-pressure rocks) are thrust on top of the ophiolitic mélange at the LSS suture. **(e)** Ophiolitic and sedimentary mélange are ultimately thrust onto the SQT upon final collision of the two terranes. Astenospheric upwelling leads to bimodal igneous activity on both sides of Shuanghu-Tethys suture zone.

SED
7, 329–367, 2015

Tectonic evolution of the Qiangtang Terrane, Tibet

Z. Zhao et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion