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The Langjiexue Group is an *in situ* sedimentary sequence rather than an exotic block: Constraints from coeval Upper Triassic strata of the Tethys Himalaya (Qulonggongba Formation)

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Abstract The Upper Triassic Langjiexue Group in southeastern Tibet has long been an enigmatic geological unit. It belongs tectonically to the northern Tethys Himalayan zone, but provenance signatures of the detritus it contains are significantly different from those of typical Tethys Himalayan sandstones. Because the Langjiexue Group is everywhere in fault contact with Tethys Himalayan strata, its original paleogeographic position has remained controversial for a long time. According to some researchers, the Langjiexue Group was deposited onto the northern edge of the Indian passive continental margin, whereas others interpreted it as an independent block accreted to the northern Indian margin only during final India-Asia convergence and collision in the Paleocene. This study compares the Langjiexue Group and coeval Upper Triassic strata of the southern Tethys Himalayan zone (Qulonggongba Formation). Our new provenance data indicate that Qulonggongba Formation sandstones contain common felsic volcanic rock fragments, minor plagioclase, and euhedral to subhedral zircon grains yielding Late Paleozoic to Triassic ages. These provenance features compare well with those of the Langjiexue Group. Because the Qulonggongba Formation certainly belongs to the Tethys Himalayan zone, the provenance similarity with the Langjiexue Group indicates that the latter is also an *in situ* Tethys Himalayan sedimentary sequence rather than part of an exotic block. Volcanic detritus including Late Paleozoic to Triassic zircon grains in both Langjiexue Group and Qulonggongba Formation are interpreted to have been derived from the distant Gondwanide orogen generated by Pan-Pacific subduction beneath the southeastern margin of Gondwana. The Qulonggongba Formation, deposited above marlstones of the lower Upper Triassic Tulong Group, is overlain by India-derived coastal quartzose sandstones of the uppermost Triassic Derirong Formation. Deposition of both the Qulonggongba Formation and the Langjiexue Group were most likely controlled by regional tectonism, possibly a rifting event along the northern margin of Gondwana.

Keywords Tethys Himalaya, Provenance analysis, Langjiexue Group, Detrital-zircon geochronology, Tectonic setting, Late Triassic, Paleogeography

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1. Introduction

The vast Neo-Tethys ocean separating the Eurasia and Gondwana continents closed in the middle Paleocene as a result of continental collision between India and Asia. The long-standing debate about the possibility that independent terranes and/or intra-oceanic arcs existed within the Neo-Tethys Ocean (e.g., Aitchison et al., 2000; Li et al., 2010; van Hinsbergen et al., 2012; Hébert et al., 2012) has notably influenced our understanding of Neo-Tethyan evolution as well as of the India-Asia collision (e.g., Hu et al., 2016).

The Upper Triassic Langjiexue Group is a suite of turbidites exposed south of the Yarlung-Zangbo suture zone in the central-eastern Himalaya (Zhang et al., 2014, 2015). It tectonically belongs to the Tethys Himalayan zone, but the detritus it contains displays provenance features significantly different from those of other Tethys Himalayan sandstones. These differences include: (1) paleocurrent directions in the Langjiexue Group turbidites are mainly southwestward (Li et al., 2003a; Xu et al., 2011; Wang et al., 2016), whereas Tethys Himalayan siliciclastic strata generally show northward sediment transport across the northern passive continental margin of India (e.g., Hu et al., 2010); (2) sandstones in the Langjiexue Group contain 5–20% volcanic rock fragments and minor plagioclase. Framework petrography, heavy-minerals, and whole-rock geochemistry all consistently indicate orogenic provenance. Instead, most Tethys Himalayan siliciclastic rocks range from feldspatho-quartzose to pure quartzose, pointing to provenance from cratonic India in the south (Garzanti, 1999; Li et al., 2003b, 2004, 2011; Zeng et al., 2009; Xu et al., 2011; Sciunnach and Garzanti, 2012; Zhang et al., 2017); (3) whole-rock Nd isotopes of Langjiexue Group sandstones ($\varepsilon_{\mathrm{Nd}}(t)$ values from −7 to −3) indicate a more juvenile source than for most Tethys Himalayan sediments ($\varepsilon_{\mathrm{Nd}}(t)$ around −15) (Dai et al., 2008); (4) detrital zircons yielding Late Paleozoic to early Mesozoic ages (400–200 Ma, mostly clustered at 280–220 Ma with peak at ~245 Ma) and $\varepsilon_{\mathrm{Hf}}(t)$ values between −5 and 10 occur in the Langjiexue Group (Aikman et al., 2008; Li et al., 2010, 2016; Cai et al., 2016; Wang et al., 2016; Cao et al., 2018; Fang et al., 2018) but are rare in most Tethys Himalayan strata (e.g., Hu et al., 2010); (5) chrome spinels with relatively low Al_2O_3 (5–30%) and TiO_2 (0–2%) (Li et al., 2016) suggesting arc-basalt or mantle-peridotite sources (Kamenetsky et al., 2001) are common only in the Langjiexue Group.

Since the first report of 400–200 Ma detrital zircons in the Langjiexue Group (Aikman et al., 2008), many provenance studies have been carried out on this unit, and several different paleogeographic scenarios have been hypothesized (as discussed in Wang et al., 2016; Cao et al., 2018; Ao et al., 2018). Because magmatic rocks of Late Paleozoic to Triassic age are not typical of the Indian subcontinent, the tectonic setting and provenance of the Langjiexue Group has remained controversial. The core of the argument is whether the Langjiexue Group represents *in situ* sediments or part of an exotic block. According to some researchers, the Langjiexue Group was originally deposited onto the distal continental margin of northern India and derived from Gondwana (Cai et al., 2016; Li et al., 2016; Wang et al., 2016; Cao et al., 2018; Fang et al., 2018), whereas others interpreted it as part of an exotic terrane deposited in the forearc region of either the Lhasa block or an intra-oceanic arc, and accreted to the northern Indian margin only during the final convergence and collision between India and Asia (Li et al., 2010, 2014; Ao et al., 2018). Because the Langjiexue Group is everywhere in fault contact with Tethys Himalayan strata without any evidence of either a suture zone or direct depositional relationship, the argument is still hotly debated.

In order to solve the conundrum and to constrain the tectonic setting of the Langjiexue Group, rather than focusing on the Langjiexue Group itself, we chose to study the coeval shallow-marine strata of the southern Tethys Himalayan zone. By investigating stratigraphic, sedimentological, and provenance features of the Upper Triassic sedimentary system in Tethys Himalaya, we discovered that sandstones within the Qulonggongba Formation exposed in the Nyalam-Tingri areas display identical provenance to the Langjiexue Group turbidites, and thus could conclude that the latter represent *in situ* Tethys Himalayan deposits rather than part of an exotic block.

2. Geological background

The middle Paleocene India-Asia continental collision initiated the Himalayan orogeny and the Cenozoic tectonic evolution of the Tibetan Plateau (Hu et al., 2015; Figure 1a). The boundary between the Indian and Asian continental margins is represented by the Yarlung-Zangbo suture zone, including forearc ophiolites and accretionary mélange (Allègre et al., 1984; Cai et al., 2012; An et al., 2017; Wang et al., 2017). North of the Yarlung-Zangbo suture, the Gangdese arc and the Xigaze forearc basin document magmatic and sedimentary evolution during northward subduction of Neo-Tethyan oceanic lithosphere beneath the Asian continent (Dürr, 1996; Ji et al., 2009; Zhu et al., 2011a; Wang et al., 2012; An et al., 2014; Hou et al., 2015; Orme and Laskowski, 2016). South of the Yarlung-Zangbo suture, the Tethyan Himalayan zone—further subdivided into northern and southern subzones by the Gyirong-Kangmar Thrust (Ratschbacher et al., 1994)—preserves Lower Paleozoic to Eocene strata deposited onto the northern Indian passive continental margin (Jadoul et al., 1998; Garzanti, 1999; Hu et al., 2012). The northern Tethys Himalaya is characterized by continental-slope to deep-sea turbidites, mudrocks, and cherts (Li et al., 2005; Hu et al., 2008; Wang et al., 2011), whereas the southern Tethys Himalaya mostly consists of shallow-marine carbonates and deltaic to shelfal siliciclastic rocks (Willems et al., 1996; Jadoul et al., 1998; Garzanti et al., 1998; Hu et al., 2012). South of the Tethys Himalayan zone and of the South Tibetan Detachment System lies the Higher/Greater Himalaya, consisting of Indian continental crust metamorphosed at medium to high-grade and finally incorporated into the Himalayan orogen (LeFort, 1996; Carosi et al., 2018). Further to the south lie the Precambrian to Paleogene Lesser Himalayan sedimentary and metasedimentary rocks, and Sub-Himalayan Neogene foreland basin sediments (Najman, 2006).

The Langjiexue Group in the central-eastern Himalaya tectonically belongs to the northern Tethys Himalayan zone (Figure 1a). Strata were strongly deformed during the Himalayan orogeny, and experienced partly low-grade and locally up to medium-grade metamorphism (Wang et al., 2016). The Langjiexue Group was deposited in the Carnian-Norian, as indicated by sparse ammonites and bivalves (Tibetan Bureau of Geology and Mineral Resources, 1993; Tibetan Institute of Geological Survey, 2007). It is worth noting that the Langjiexue Group was intruded by numerous diabase sills and dikes (Wang et al., 2016; Ao et al., 2018). These mafic rocks, widely documented in the Tethys Himalaya, were associated with the Lower Cretaceous Comei-Bunbury large igneous province erupted during final breakup of eastern Gondwana (Zhu et al., 2009a).

3. Stratigraphy and sedimentology

This study investigates the southern Tethys Himalayan subzone in the Nyalam-Tingri area of southern Tibet, and focuses specifically on the topmost part of the Tulong Group and on the overlying Qulonggongba and Derirong Formations (equivalent to the Tarap Formation and Zhamure Sandstone of Jadoul et al., 1998; figure 3 in Sciunnach and Garzanti, 2012) (Figure 1). Three stratigraphic sections (Tulong in the Nyalam area, Qiecun and Jiawula in the Tingri area) were measured, and facies analysis was carried out (Figure 1b). The Tulong section is complete (Figures 2 and 3a), whereas only the middle-upper parts of the succession are exposed in the Qiecun and Jiawula sections (Figure 2).

3.1 The topmost Tulong Group

The topmost part of the Tulong Group comprises thick to

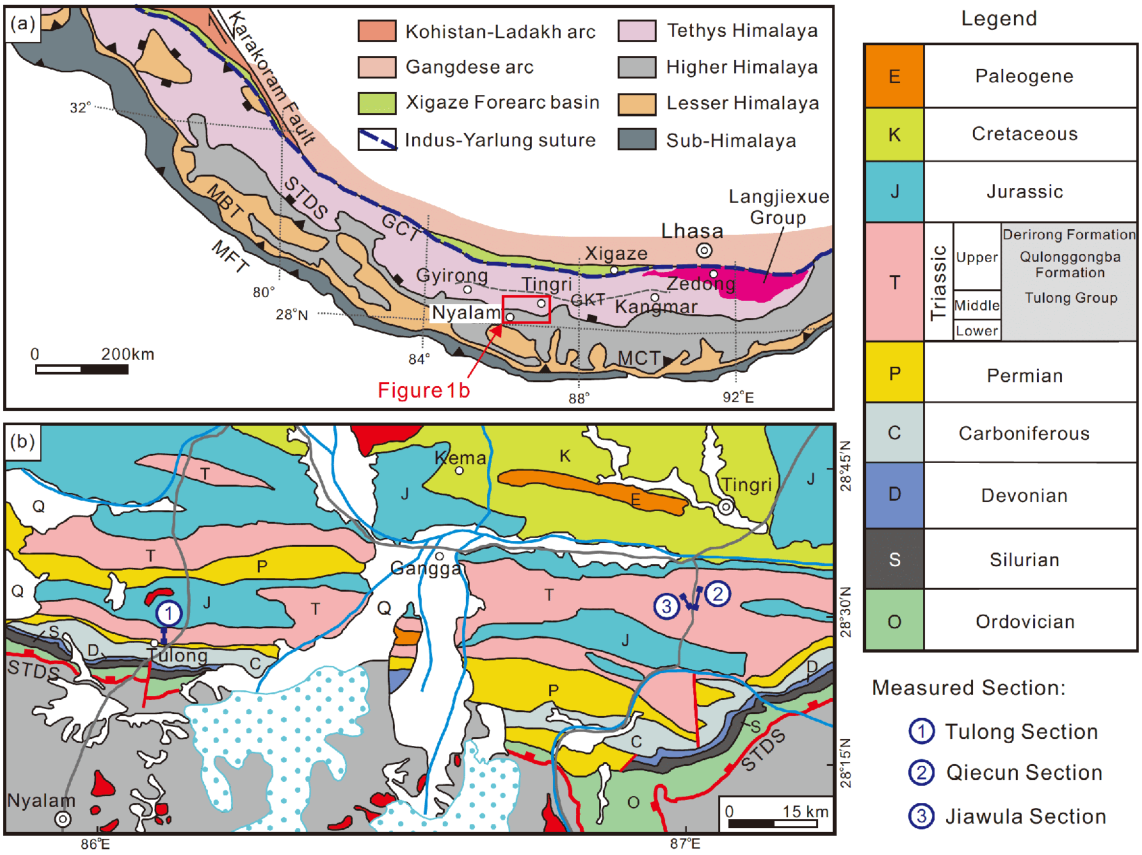


Figure 1 Geological map of the study area. (a) Simplified tectonic map of the Himalayan orogen (modified from Yin, 2006). GCT, Great Counter Thrust; STDS, South Tibetan Detachment System; MCT, Main Central Thrust; MBT, Main Boundary Thrust; MFT, Main Frontal Thrust; GKT, Gyirong-Kangmar Thrust; (b) geological map of Nyalam-Tingri areas (modified after the 1:1 500 000 geological map of Tibet and adjacent areas).

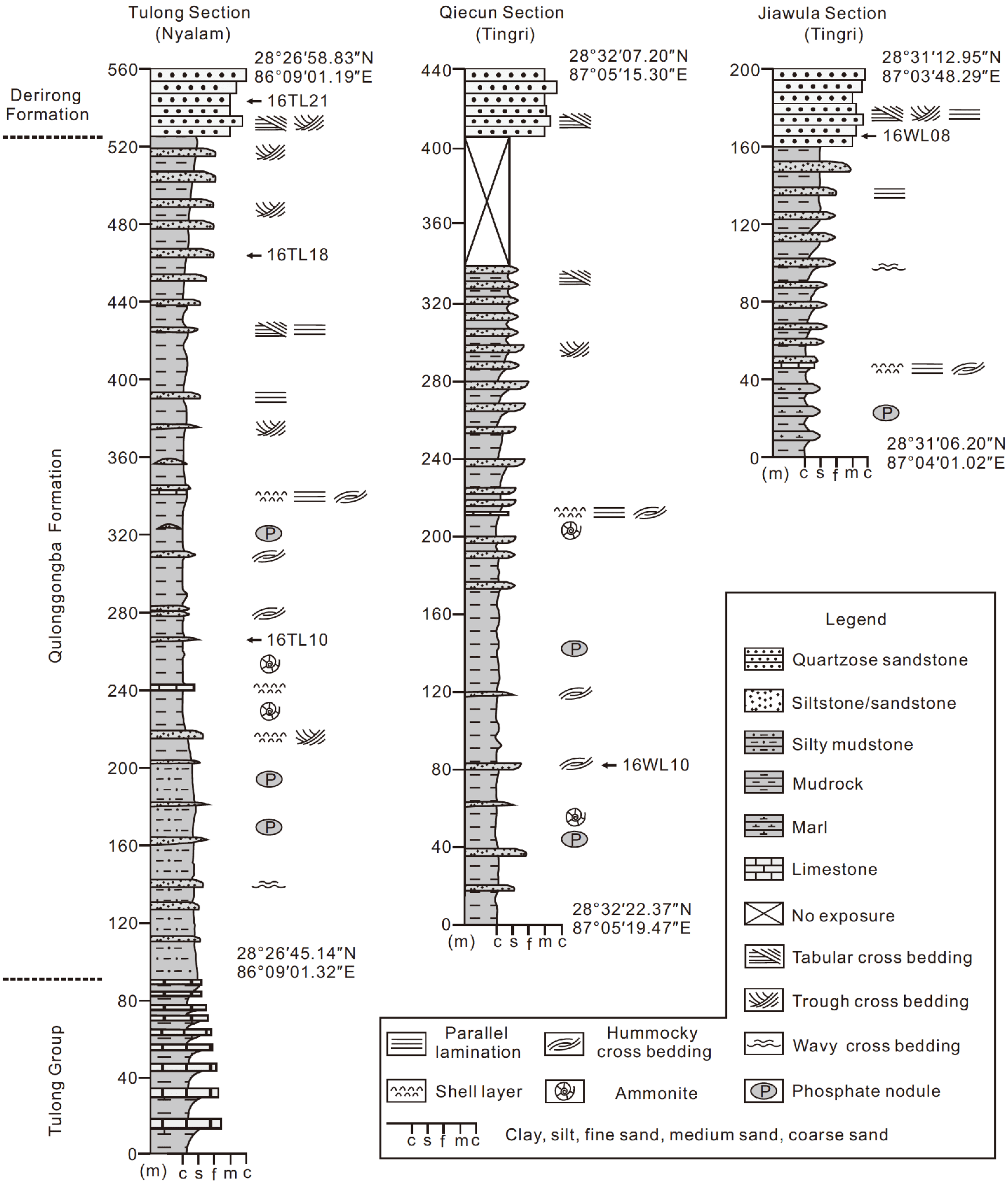


Figure 2 Measured stratigraphic sections in the Nyalam-Tingri area. GPS position, sedimentary structures, and samples analysed for detrital-zircon geochronology are indicated.

medium-bedded, black (weathered to yellowish) silty bioclastic packstone and dark-gray marlstone (Figure 3b). Packstones are well bedded (mainly 15 to 60 cm-thick), laterally continuous and contain bivalves, gastropods, ostracods and rare echinoderm fragments (Figure 4a and 4b). Marlstones are rich in small phosphate nodules and burrows. Marlstones and packstones are arranged in upward-coarsening cycles (Figure 3c). The sharp upper surface of the packstone layer at the top of each cycle is overlain by marlstone of the overlying cycle. Cycle thickness decreases up-section (4–0.5 m), where fossils decrease in abundance and terrigenous detritus increases.

Lithologies and low-diversity fossils indicate an oxygenated, low-energy lagoonal environment in clastic marginal-marine setting. Depositional age was constrained as late Carnian by conodont assemblages (Garzanti et al., 1998).

3.2 Qulonggongba Formation

The Qulonggongba Formation, in transitional contact with the underlying Tulong Group, is about 430 m thick in the Tulong section. The lower part consists of ~60-m-thick in-

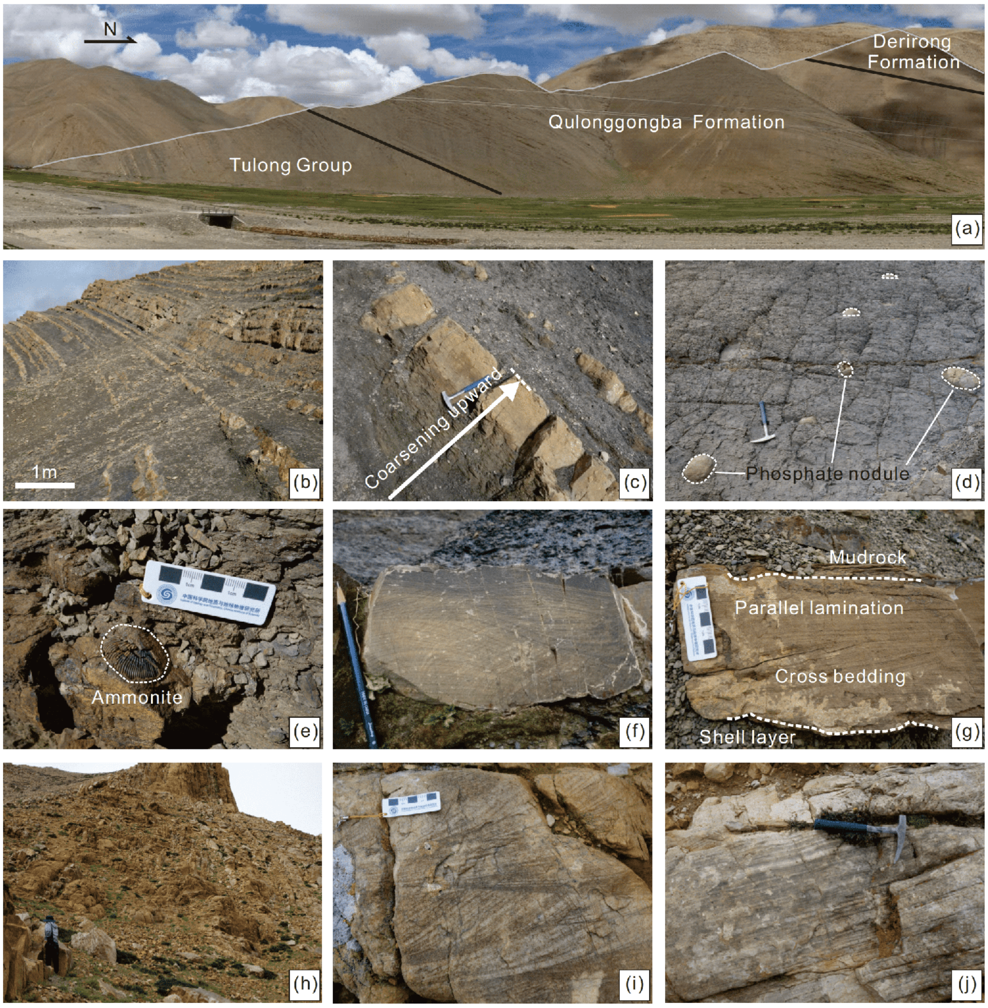


Figure 3 Field photographs. (a) Panoramic view of the Tulong section near Nyalam; (b) interbedded marls and silty bioclastic packstones (topmost Tulong Group, Tulong section); (c) coarsening-upward cycles from marl to silty bioclastic packstone (Tulong Group, Tulong section); (d) phosphate nodules in black shale (lower-middle Qulonggongba Formation, Qiecun section); (e) ammonite (lower Qulonggongba Formation, Tulong section); (f) hummocky lamination in fine-grained sandstone (middle Qulonggongba Formation, Qiecun section); (g) storm sequence (middle Qulonggongba Formation, Tulong section); (h) quartzose sandstones (Derirong Formation, Tulong section); (i) trough lamination in quartzose sandstone (Derirong Formation, Tulong section); (j) low-angle planar oblique lamination in quartzose sandstone (Derirong Formation, Tulong section).

terbedded fine-grained gray to black sandstone, siltstone, and silty mudstone. Sandstones are medium to thick-bedded (mostly ~30-cm-thick), moderately well sorted, and calcite-cemented. Sedimentary structures include parallel, current-ripple, and trough lamination. Silty mudrocks contain phosphate nodules, ammonites, and burrows (Figure 3d and 3e). Shell-rich interlayers are observed locally. The middle part of the unit (~260-m-thick) consists of dominant black or greenish-gray silty mudrocks and minor dark gray (weathered to yellowish), thin-bedded or lenticular, fine-grained sandstones. Hummocky lamination is common in sandstone beds (Figure 3f), and complete storm-surge sequences comprising (from bottom to top) a basal shell-rich layer, plane-parallel laminae, ripples, and upper parallel laminae were observed locally (Figure 3g). Mudrocks are rich in ammonites, phosphate nodules, and burrows. Sandy limestone beds including abundant bioclasts are also present. The upper part of the unit consists of gray-black silty shale and siltstone interbedded with gray-black (weathered to yellowish-brown), medium to thick-bedded, fine-grained sandstone beds mostly 20–60 cm-thick and increasing up-section in frequency and thickness. Tabular and trough oblique lamination indicate sediment transport towards the west-northwest; parallel lamination also occurs.

The lower Qulonggongba Formation documents prominent terrigenous supply in shelfal environments, as indicated by abundant fossils including ammonites. The middle Qulonggongba Formation was deposited in a low-energy inner shelf environment frequently affected by storm events. The upper Qulonggongba Formation shows a coarsening- and shallowing-upward trend, suggesting progradation in littoral environments. The age of the Qulonggongba Formation is constrained to the early Norian by ammonoid assemblages (Jadoul et al., 1998).

3.3 Derirong Formation

The >40 m-thick Derirong Formation conformably overlies the Qulonggongba Formation and consists of gray to yellowish and mainly well sorted quartzose sandstones with minor interlayered black mudrocks. Sandstones are medium- to thick-bedded (0.1–1 m), commonly lenticular and deposited above scoured surfaces. Sedimentary structures include planar and low-angle tabular lamination indicating northeastward to northwestward paleocurrents (Figure 3j) and minor parallel or trough lamination (Figure 3i). Pebble-sized clasts of black mudrock may occur at the base of sandstone beds. Plants and bivalves are locally observed. The Derirong Formation was deposited in high-energy beach environments. Depositional age is constrained as late Norian to Rhaetian by stratigraphic position and occurrence of a few bivalves (Tibetan Bureau of Geology and Mineral Resources, 1993).

The Upper Triassic stratigraphic succession exposed in the Nyalam-Tingri area shows shallow-marine sedimentary facies typical of the southern Tethys Himalaya (Jadoul et al., 1998; Garzanti et al., 1998) and records a transgressive-regressive cycle from lagoonal environments for the uppermost Tulong Group, to inner shelf for the Qulonggongba Formation and finally coastal settings for the Derirong Formation. The succession was deposited roughly at the same time as the Langjiexue Group.

4. Analytical methods

Sandstone petrography and U-Pb geochronology and Hf isotopic signatures of detrital zircons were used jointly in this study to trace provenance of siliciclastic sediments. Monocrystalline (Qm) and polycrystalline (Qp) quartz, plagioclase (Pl) and potassium (Kf) feldspars, and sedimentary (Ls), volcanic (Lv), and metamorphic (Lm) lithic fragments were identified and point-counted in thin-sections under the microscope following the Gazzi-Dickinson method (Ingersoll et al., 1984). About 420 points were counted per sample. Data are given in the Appendix Table S1 (http://link.springer.com). Detrital zircons were separated from five relatively coarse-grained sandstone samples using heavy-liquid and magnetic techniques. Single zircon grains were handpicked randomly, mounted in epoxy resin, and finally polished to a flat surface for analysis. Cathodoluminescence (CL) images were obtained to reveal the internal structures of zircons.

U-Pb dating of detrital zircons and Hf isotopic analyses were conducted at the State Key Laboratory of Lithosphere Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Data are given in the Appendix Tables S2 and S3. U-Pb dating was conducted on an Agilent 7500a Q-ICP-MS equipped with a 193-nm excimer ArF laser-ablation system (GeolasPlus) according to Xie et al. (2008). The 44 or 32 μm laser spots (in diameter) were used depending on the size of zircon grains. Ages were determined from raw count rates for ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U using the GLITTER program (Griffin et al., 2008). We considered ^{206}Pb/^{238}U ages for grains younger than 1000 Ma and ^{207}Pb/^{206}Pb ages for grains older than 1000 Ma. Single ages with >10% discordance or >5% 1σ error were excluded. Zircon Hf isotope analysis was carried out on a Neptune Multi-Collector ICP-MS equipped with the Geolas 193 laser-ablation system. Details on instrumental conditions and data acquisition are found in Wu et al. (2006).

5. Results

5.1 Sandstone petrography

Sandstones from the Qulonggongba Formation are fine-grained and range in composition from litho-quartzose volcaniclastic to feldspatho-litho-quartzose and quartz-rich feldspatho-quartzose (average modal composition Q:F:L=72:10:18; Figure 5a; Appendix Table S1). Authigenic phyllosilicates and carbonates are widespread (Figure 4c and 4d). Quartz grains, mostly monocrystalline and angular to subrounded, constitute 63–83% of total framework grains. Some grains show authigenic overgrowth. Lithic fragments constitute 10–30% of framework grains and are derived mainly from felsic volcanic rocks and subordinately from pelitic to low-rank metapelitic and carbonate rocks (Figure 5b). Feldspars (1–6%) are mainly twinned plagioclase with a few strongly altered grains ascribed to alkali feldspar. Zircon, muscovite, hornblende, rutile, and magnetite also occur.

Sandstones from the Derirong Formation are medium- to coarse-grained or pebbly (Figure 4e and 4f) and quartzose in composition (Figure 5a; Appendix Table S1). Quartz grains are mostly monocrystalline, well sorted and rounded, and cemented by syntaxial quartz overgrowths. Rare plagioclase and metapelite lithics (<5%) were observed. The heavy-mineral assemblage is dominated by zircon, rutile, and tourmaline.

5.2 U-Pb age of detrital zircons and Hf isotopes

Sandstone samples from the Qulonggongba Formation yielded 170 single zircon ages (16WL10, 16TL10, and 16TL18; Appendix Table S2), with main age cluster at 700–450 Ma (late Neoproterozoic-early Paleozoic, age peak at ~550 Ma) and a subordinate broad cluster at 1400–850 Ma (Mesoproterozoic-early Neoproterozoic). A few Archean to Paleoproterozoic ages cluster at ~1850 Ma and ~2500 Ma. Significantly, 14 zircons (~8% of total grains) yielded late Paleozoic-early Mesozoic ages between 397 Ma and 207 Ma, clustering at 260–207 Ma with peak at ~225 Ma (Figure 6).

Two samples from the Derirong Formation (16WL21 and 16WL08) yielded 173 single zircon ages (Appendix Table S2), all older than 470 Ma. The main cluster occurs at 650–

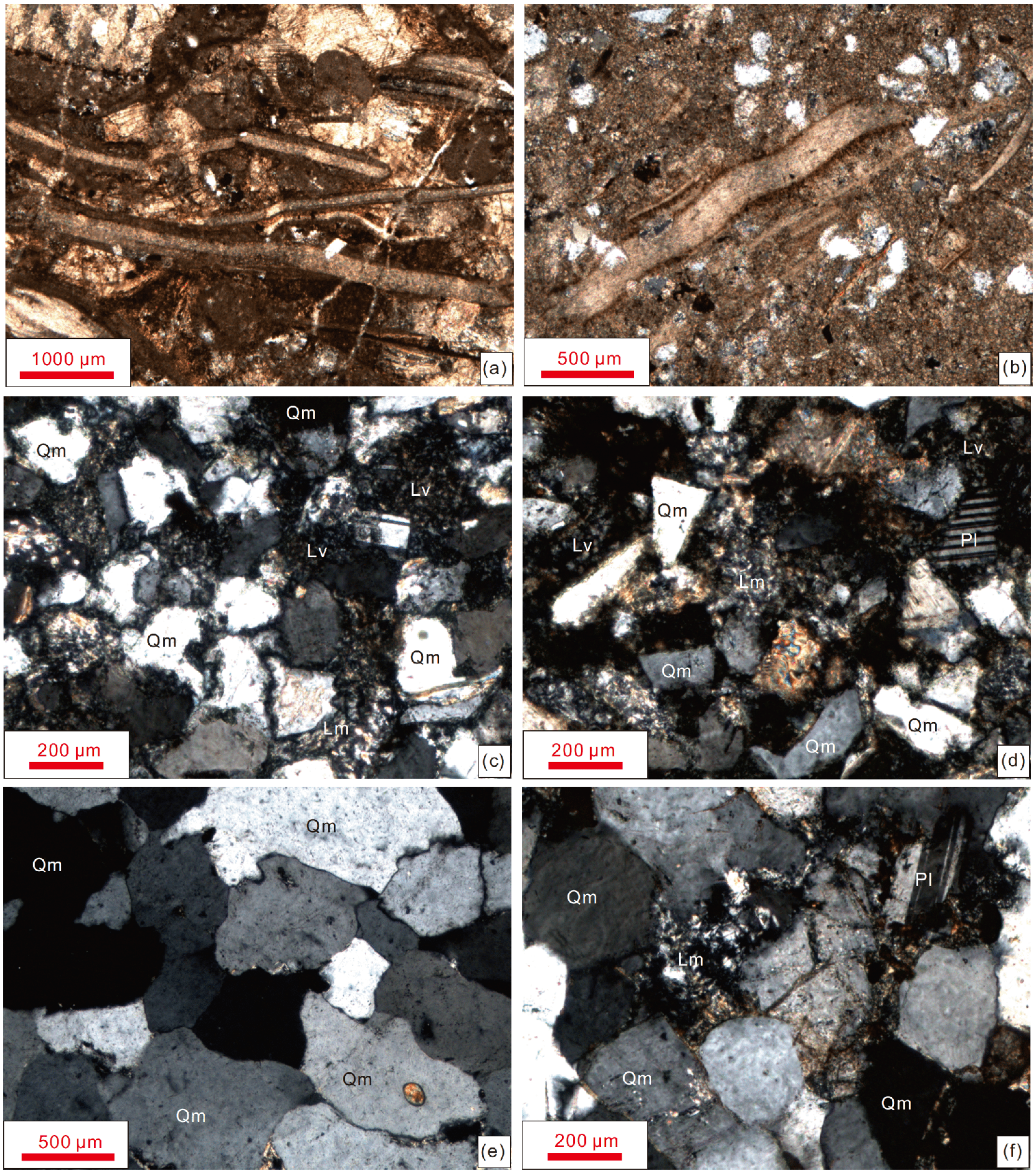


Figure 4 Photomicrographs. (a), (b) Silty bioclastic limestones (Tulong Group, samples 17TL04 and 17TL03); (c), (d) litho-quartzose volcaniclastic sandstone (Qulonggongba Formation, samples 17TL17 and 16WL11); (e), (f) pure quartzose sandstone (Derirong Formation, samples 16TL21 and 16WL14).

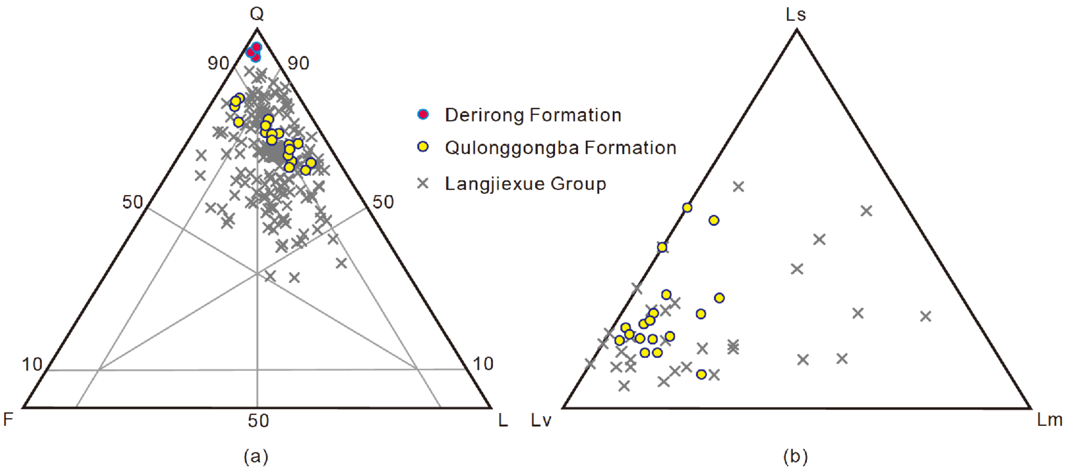
470 Ma with peak at 515 Ma. A subordinate cluster at 1250–720 Ma with peak at ~950 Ma and a minor cluster at ~2450 Ma also occur (Figure 6).

Hf isotopic analysis was performed on late Paleozoic-early Mesozoic detrital zircons from the Qulonggongba Formation (Appendix Table S3). These zircons have well-developed oscillatory compositional zoning, suggesting magmatic origin (Figure 7; Corfu et al., 2003; Wu and Zheng, 2004), and yielded $\varepsilon_{\mathrm{Hf}}(t)$ values mostly between −3 and 4, with corresponding crustal mode age ($T_{\mathrm{DM}}{}^{\mathrm{C}}$) of 1.5−1.0 Ga. Three zircon grains with Late Triassic age (226–214 Ma) yielded higher $\varepsilon_{\mathrm{Hf}}(t)$ values of 11 to 17, with corresponding $T_{\mathrm{DM}}{}^{\mathrm{C}}$ age of 0.15−0.76 Ga (Figure 8).

6. Discussion

6.1 Comparison among Upper Triassic Tethys Himalayan units

Provenance signatures of the Qulonggongba Formation and the Langjiexue Group compare well, as shown in Figures 5, 6, and 8. Sandstones from both units are feldspatho-litho-quartzose on average and mainly range in composition from litho-quartzose to feldspatho-quartzose, overlapping very largely on the QFL diagram (Figure 5a). Lithic fragments are mainly felsic volcanic (Figure 5b) and feldspars are dominantly plagioclase. The U-Pb age-spectra of detrital zircons are very similar, with virtually identical early Paleozoic-



(a) (b)

Figure 5 Sandstone petrography. (a) QFL diagram (fields after Garzanti, 2016). Q, quartz; F, feldspar; L, lithic fragments; (b) Ls-Lv-Lm diagram. Ls, sedimentary lithics; Lv, volcanic lithics; Lm, metamorphic lithics. Data for the Langjiexue Group from Li et al. (2004), Li et al. (2010), Xu et al. (2011), Cai et al. (2016), Zhang et al. (2017), and Wang et al. (2016).

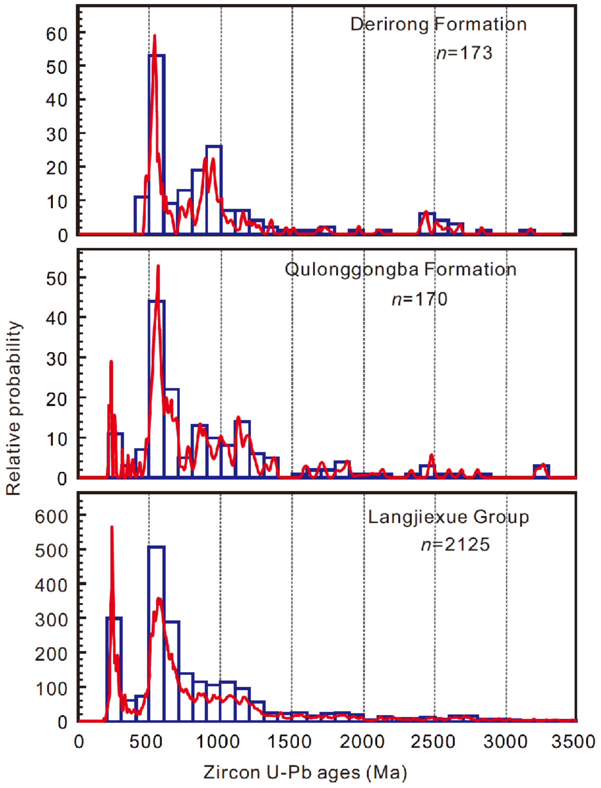


Figure 6 Relative U-Pb age probability for detrital zircons. Data for the Langjiexue Group from Li et al. (2010), Cai et al. (2016), Li et al. (2016), and Wang et al. (2016).

Precambrian peaks. Late Paleozoic-early Mesozoic zircon grains are present in both units (Figure 6) and all display euhedral to subhedral shape and well-developed oscillatory compositional zoning, suggesting a first-cycle magmatic origin (Figure 7; Wang et al., 2016). The $\varepsilon_{\mathrm{Hf}}(t)$ values and the corresponding crustal mode age ($T_{\mathrm{DM}}^{\mathrm{C}}$) of these zircons are also similar; only a few grains from the Qulonggongba Formation have relatively depleted isotopic composition (Figure 8).

These common provenance fingerprints suggest that the Qulonggongba Formation and the Langjiexue Group may belong to the same depositional system, and that their sedimentological differences may simply reflect the different — shelfal versus continental slope to deep-sea-depositional environment. If this is correct, because undoubtedly the Qulonggongba Formation belongs to the Tethys Himalaya, then the Langjiexue Group must also belongs to the Tethys Himalaya rather than to an exotic block.

The Nieru Formation, another Upper Triassic stratigraphic unit of the Tethys Himalaya, was named after the black silty shales, slates, and interlayered fine-grained quartzose sandstones exposed near the Nieru village in Kangmar (Tibetan Bureau of Geology and Mineral Resources, 1993). During the 1:250000 regional geological mapping, Upper Triassic turbidites cropping out in the Nagarze-Longzi areas (Figure 9a and 9b) were also assigned to the Nieru Formation, and distinguished from the low-grade Langjiexue Group turbidites exposed closer to the Yarlung-Zangbo suture. According to Li et al. (2011), however, these strata should be assigned to the Langjiexue Group, because they have similar lithology, sedimentary structures, fossils, petrographic composition, whole-rock geochemistry, and detrital zircon U-Pb ages and Hf isotopic fingerprints. Similarly, the Nieru Formation in the type Kangmar area, mainly consisting of black mudrocks with minor hummocky-laminated sandstones (Figure 9c and 9d), compares well with the Qulonggongba Formation. In fact, U-Pb age-spectra of detrital zircons in the Nieru Formation, Qulonggongba Formation, and Langjiexue Group are all very similar, indicating that these three units all belong to the same sedimentary system deposited onto the northern Indian margin during the Late Triassic (Cai et al., 2016; Wang et al., 2016).

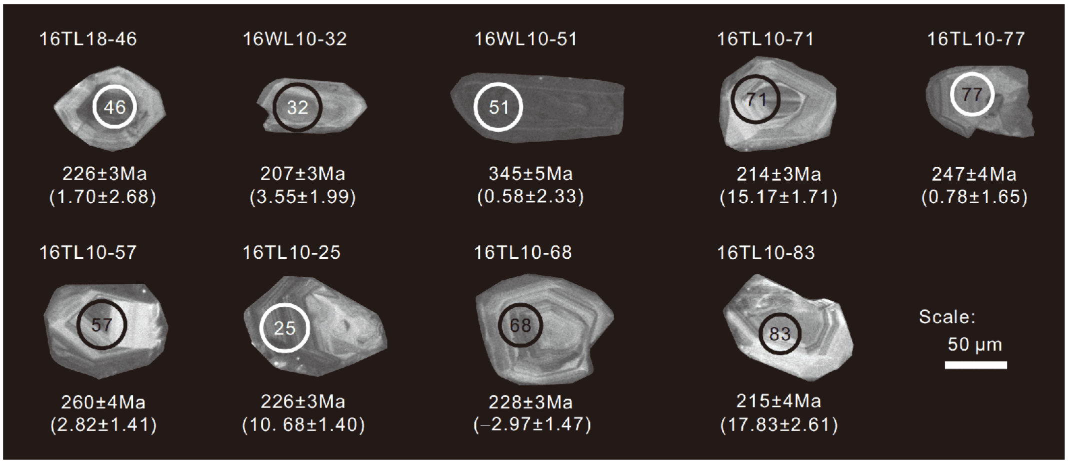


Figure 7 Representative cathodoluminescence images of late Paleozoic-early Mesozoic detrital zircons from the Qulonggongba Formation. Circles indicate the analytical spot; the U-Pb age and $\varepsilon_{\mathrm{Hf}}(t)$ value of each grain is shown.

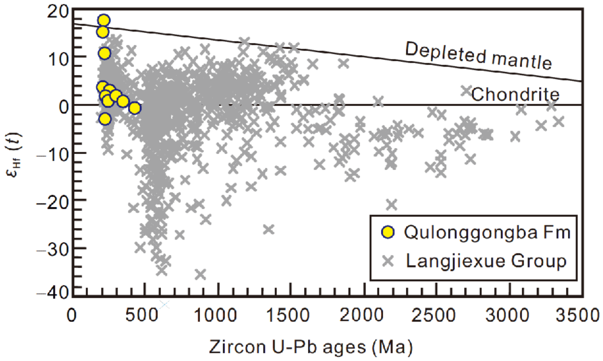


Figure 8 U-Pb age vs. $\varepsilon_{\mathrm{Hf}}(t)$ plot for late Paleozoic-early Mesozoic detrital zircons from the Qulonggongba Formation. Data from the Langjiexue Group (after Li et al., 2010; Li et al., 2016; and Wang et al., 2016) are shown for comparison.

In contrast, Ao et al. (2018) proposed that the Langjiexue Group, together with the whole of the Tethys Himalaya, represents an accretionary wedge assembled in the trench during northward subduction of Neo-Tethyan oceanic lithosphere and eventually accreted onto the northern Indian margin during the India-Asia collision. However, stratigraphic and sedimentological studies indicate that the Langjiexue Group strata represent a largely regular stratigraphic sequence (Zhang et al., 2015), and thus radically different in structure from mélange units. The supposed ‘mafic blocks’ reported from the Langjiexue Group and from other central-eastern Tethys Himalayan strata were dated as Early Cretaceous (around 130 Ma; Ao et al., 2018), and they are thus much younger than the Triassic strata in which they are contained (Tibetan Bureau of Geology and Mineral Resources, 1993; Tibetan Institute of Geological Survey, 2007). These mafic rocks represent dikes or sills belonging to the Lower Cretaceous Comei-Bunbury large igneous province, deformed and boudinaged during the Himalayan orogeny. The supposed limestone and chert blocks described by Ao et al. (2018) may also represent strata dismembered during orogenic deformation. All of these observations indicate that the Langjiexue Group is *in situ* Tethys Himalayan deposits rather than part of an accretionary wedge.

6.2 Provenance interpretation

Mainly felsic volcanic rock fragments and detrital zircons of magmatic origin yielding ages clustering between ~260 and 207 Ma provide the key to a precise provenance diagnosis for Upper Triassic clastic rocks of the central-eastern Tethys Himalaya. If the latter are indeed *in situ* sediments deposited onto the northern Indian margin, then detritus should have been derived from either India or adjacent parts of Gondwana. Late Paleozoic-early Mesozoic magmatism is however scarce around peninsular India, excepting the Lower Permian “Panjal” continental-flood basalts (Garzanti et al., 1999). This large igneous province, however, could not have represented a major source for Upper Triassic sandstones, as suggested by Cao et al. (2018), because: (1) volcanic rock fragments in Upper Triassic sandstones are mainly felsic rather than mafic; (2) late Paleozoic-early Mesozoic detrital zircons have well-developed oscillatory zoning, whereas zircons from mafic rocks generally show homogeneous internal texture (Wu and Zheng, 2004); (3) “Panjal” magmatism took place in the late Early Permian, whereas the ages of young detrital zircons in Upper Triassic sandstones are mostly later than 260 Ma with a peak at ~245 Ma; (4) “Panjal” basalts are most extensive in the western Tethys Himalaya (Garzanti et al., 1999), whereas the Langjiexue Group is only exposed in the central-eastern Tethys Himalaya; (5) chrome spinels from Upper Triassic sandstones have low Al and Ti contents, in contrast with those in continental flood basalts (Li et al., 2016). All provenance data from Upper Triassic sandstones in the Tethys Himalaya concur to indicate a long-lived magmatic-arc source (Wang

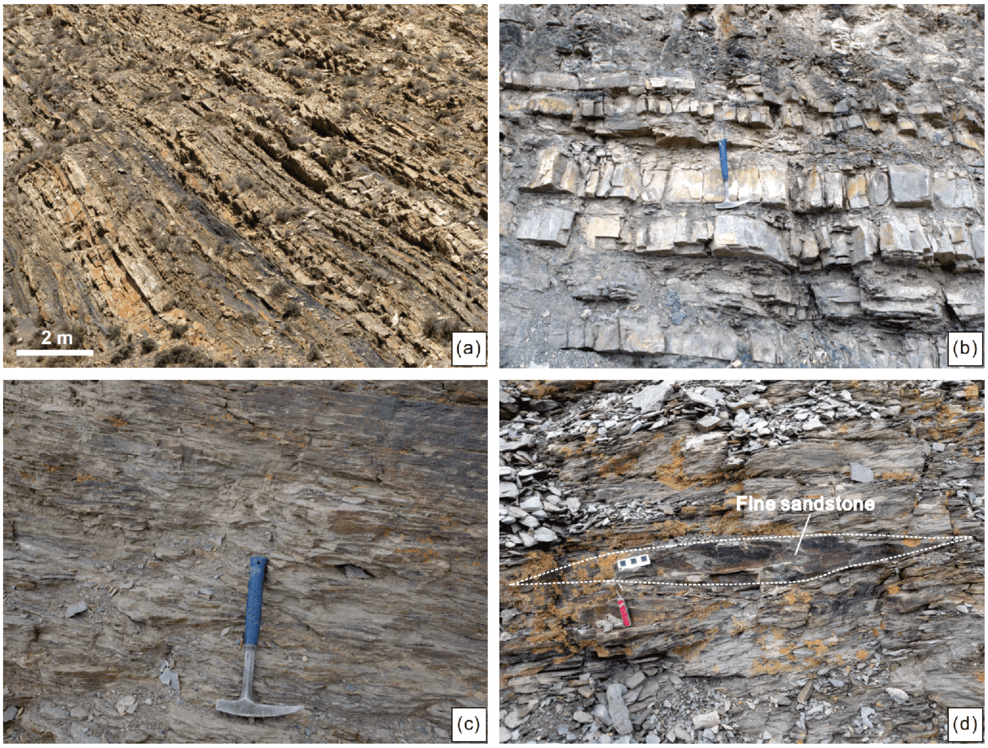
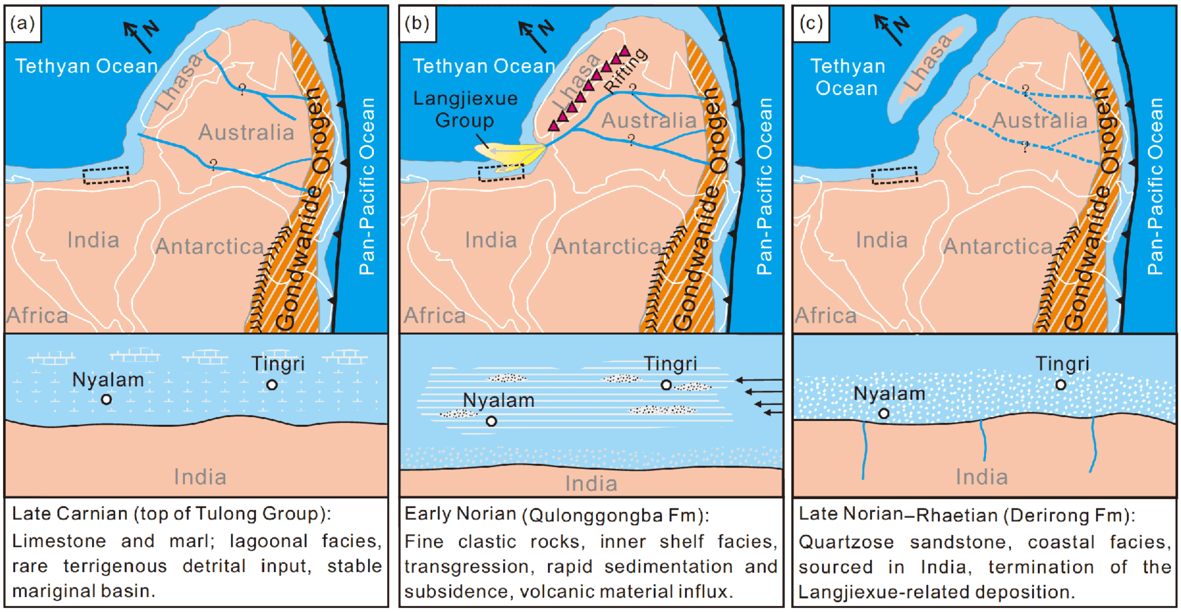


Figure 9 Field photographs of the Nieru Formation in the Tethys Himalaya. (a), (b) Turbidites in the Qiongjie-Zheguco areas were assigned to the Langjiexue Group (Li et al., 2011); (c), (d) shelfal black mudrocks, slates, and fine-grained lenticular sandstones exposed in the type locality in Kangmar.

et al., 2016). These include: (1) nearly continuous distribution of zircon ages from ~400 Ma to 200 Ma; (2) euhedral to subhedral shape and well-developed oscillatory zoning of these zircon grains; (3) $\varepsilon_{\mathrm{Hf}}(t)$ values from −5 to 10, with corresponding crustal mode ages ($T_{\mathrm{DM}}^{\mathrm{C}}$) from 1.5 Ga to 0.5 Ga; (4) common and mainly felsic volcanic rock fragments associated with minor plagioclase; (5) geochemical features of detrital Cr-spinel analogous to those in arc basalts and peridotites (Li et al., 2016).

Plate reconstructions indicate that in the Late Triassic India lay within eastern Gondwana, to the northwest of Australia and Antarctica (Figure 10). A thousand kilometer-long subduction zone existed all along the Pan-Pacific southeastern edge of eastern Gondwana, while a divergent plate margin developed along its northwestern edge (Golonka and Ford, 2000; Veevers, 2004; Cawood, 2005). The activity of this Pan-Pacific arc is well documented by magmatic and sedimentary records preserved in the eastern margin of Australia, Antarctic Orogen, New Zealand, Papua, and New Guinea (e.g., Cawood et al., 1999; Sircombe, 1999; Elliot and Fanning, 2008; Gunawan et al., 2012) and the existence of a large Andean-type Gondwanide orogen along the southeastern active margin of Gondwana at latest Paleozoic to early Mesozoic times as a result of continuing convergence and compressive tectonics has long been documented (Carey and Browne, 1938; Collins, 1991; Holcombe et al., 1997). The southeastern active margin of Gondwana thus represents a most plausible source of the volcanic detritus including late Paleozoic-early Mesozoic zircons that characterizes the Langjiexue Group and related sedimentary system (Figure 10b; Cai et al., 2016; Wang et al., 2016). The U-Pb ages and Hf isotopic signatures of zircons contained in these rocks (Kemp et al., 2009; Jeon et al., 2014) compare well with those of detrital zircons in the Langjiexue Group and related sedimentary units.

If the magmatic arc and Gondwanide orogen along the Pan-Pacific side of Gondwana was indeed the source of the Langjiexue Group and related sedimentary units, then detritus should have been transported all across the supercontinent for a few thousands of kilometers at least before being finally deposited along the Neo-Tethyan margin of India. Although supporting evidence cannot be presented yet, transcontinental sediment transport is far from unusual on Earth today (Dickinson, 1988). The Gondwanide orogen must have acted as a watershed that forced detritus eroded along its northwestern flank to be transported westward toward the Neo-Tethyan margin. Such a paleo-drainage pattern should have been similar to that of modern South America, where the Amazon River carries huge volumes of sediment from the Andes all the way to the Atlantic passive margin on the other side of the continent. Detritus from the Gondwanide orogen must have mixed with detritus eroded from Gondwana basement and cover rocks along the way, which explains the presence of numerous early Paleozoic and



Late Carnian (top of Tulong Group): Limestone and marl; lagoonal facies, rare terrigenous detrital input, stable mariginal basin.

Early Norian (Qulonggongba Fm): Fine clastic rocks, inner shelf facies, transgression, rapid sedimentation and subsidence, volcanic material influx.

Late Norian–Rhaetian (Derirong Fm): Quartzose sandstone, coastal facies, sourced in India, termination of the Langjiexue-related deposition.

Figure 10 Late Triassic paleogeographic scenario envisaged to explain transcontinental sediment transport across eastern Gondwana toward the northern Indian margin from late Carnian (a), to Norian (b), and Rhaetian (c) times. Plate reconstruction after Golonka and Ford (2000), Veevers (2004), and Cawood (2005).

Precambrian zircons in the Langjiexue Group and related sedimentary units. Transcontinental sediment transport by a big-river system is also implied by the huge turbiditic fan documented by the Langjiexue Group.

Although at the present state of knowledge long-distance sediment dispersal from the Gondwanide orogen is only a working hypothesis, and the location and orientation of the inferred paleo-drainage is unconstrained, our scenario does provide a plausible explanation for provenance of the Langjiexue Group, whereas all other models are incompatible with the available provenance data (see discussion in Wang et al., 2016).

The Derirong Formation overlying the Qulonggongba Formation comprises quartzose sandstones lacking volcanic detritus and late Paleozoic-early Mesozoic zircons. U-Pb zircon-age spectra are consistent with those from most other Tethys Himalayan strata, indicating provenance from peninsular India (e.g., Cawood and Buchan, 2007; Gehrels et al., 2011). The stark contrast in petrographic composition and detrital-zircon ages between the Qulonggongba and Derirong Formation reveal drastic provenance changes documented by Tethys Himalayan strata have taken place in the latest Triassic.

6.3 Paleogeographic scenario and Sedimentary evolution

Upper Triassic strata of the Tethys Himalaya testify to mark facies and provenance changes. Supply of volcanic detritus to the topmost Tulong Group and Qulonggongba Formation was associated with transgression and increasing tectonic subsidence and sedimentation rates (Jadoul et al., 1998; Sciunnach and Garzanti, 2012). During deposition of the quartzose Derirong Formation, instead, a shallowing-upward trend points to a regional regression and initiation of a more quiescent stage continued throughout the Early Jurassic as documented by sedimentation of the Kioto carbonate platform all along the Tethys Himalaya.

The short-lived deposition of the Qulonggongba Formation and Langjiexue Group must have been controlled by a regional tectonic event. The rapid change in Tethys Himalayan sedimentary patterns at this time have long been related to tectonic extension along the northern Gondwanan margin (Gaetani and Garzanti, 1991; Ogg and von Rad, 1994). Because of the low stretching factor, limited change of paleo-water depth, and absence of major local magmatism, Sciunnach and Garzanti (2012) interpreted this paleotectonic change as the echo of tectonic rejuvenation in distant regions of Gondwana.

Another factor that needs consideration is that the Lhasa block may have drifted away from Gondwana during the Late Triassic (Zhu et al., 2009b, 2011a). In traditional plate reconstructions, the Lhasa block is preferentially placed adjacent to northern India (e.g., Yin and Harrison, 2000). However, U-Pb age-spectra of detrital zircons contained in Paleozoic-early Mesozoic sandstones of the Lhasa Block are distinct from those in coeval Tethys Himalayan strata, but similar to those in northwestern Australia (Zhu et al., 2011b; Wang et al., 2016). This is one main reason why we prefer the alternative paleogeographic model that envisages the Lhasa Block as originally connected instead to northwestern Australia (Audley-Charles, 1983; Zhu et al., 2011b) (Figure

10a–10c). In this case, Upper Triassic-Lower Jurassic volcanic rocks preserved on the northwest margin of Australia (Lewis and Sircombe, 2013) may be associated with rifting of the Lhasa Block.

The following evolution of depositional systems is envisaged for the studied Upper Triassic succession of the central-eastern Tethys Himalaya:

(1) Late Carnian (topmost Tulong Group; Figure 10a). The mature passive margin developed on the northern edge of peninsular India hosted mainly carbonate sediments with limited terrigenous supply. Rivers sourced in the far away Gondwanide orogen flowed northward and westward to feed the northwestern Gondwana margin. The finding of late Paleozoic-early Mesozoic detrital zircons in Upper Triassic strata as far as the Lhasa block (e.g., the Mailonggang Formation; Li et al., 2014; Li et al., 2016; Wang et al., 2016) and the northwestern margin of Australia (e.g., Mungaroo Formation; Lewis and Sircombe, 2013) is consistent with this scenario.

(2) Early Norian (Qulonggongba Formation; Figure 10b). Rifting along the northwestern Australian margin and associated magmatism induced regional thermal uplift and formation of relief which forced rivers to be deflected southwestward, carrying detritus from the Gondwanide orogen to as far as the northern Indian margin. This is somewhat analogous to the East African rift system, which forced the Nile River to flow northward along the strike of the rift to eventually reach the Mediterranean Sea (Garzanti et al., 2015). As a distant response to rifting, tectonic subsidence and transgression occurred on the Indian margin, where sedimentation rates increased significantly because of notably increased terrigenous supply. Paleocurrent directions measured from the Qulonggongba Formation and the Langjiexue Group are mainly westward to southwestward (Li et al., 2003a; Xu et al., 2011; Wang et al., 2016), which is consistent with this paleogeographic model.

(3) Late Norian-Rhaetian (Derirong Formation; Figure 10c). The end of the rifting event that affected northwestern Gondwana led to regression along the northern Indian margin. Detritus from the Gondwanide orogen no longer entered the basin, and sandstones rich in volcanic detritus were replaced by quartzose sediments derived from India. Reorganization of the paleo-drainage system may have been caused by thermal subsidence following the rifting event but also affected by other tectonic events associated with rifting in southeastern Gondwana and collapse of the Gondwanide orogen (Veevers, 2004).

Although highly uncertain, such speculations may help to promote future investigations needed to complement the information obtained on the Upper Triassic sedimentary system of the northern Indian margin with the geological record of eastern Gondwana as a whole, in order to achieve a comprehensive understanding of Late Triassic paleotectonic evolution and a satisfactory reconstruction of paleo-drainage systems across eastern Gondwana.

7. Conclusions

The paleogeographic context and provenance of the Langjiexue Group, a rather enigmatic stratigraphic unit exposed close to the India-Asia suture zone, have remained controversial for a long time. In the present study we have compared the sedimentary and provenance features of Upper Triassic strata in the southern Tethys Himalaya—including the topmost Tulong Group and the Qulonggongba and Derirong Formations—with the Langjiexue Group of the northern Tethys Himalaya. The following conclusions are reached:

(1) The topmost Tulong Group consists of marlstone and silty bioclastic packstone deposited in lagoonal to shallow-marine environments, the Qulonggongba Formation includes terrigenous mudrocks and fine-grained sandstones deposited on an inner shelf, and the Derirong Formation consists of quartzose sandstones deposited in coastal settings.

(2) Sandstones from the Qulonggongba Formation contain common felsic volcanic rock fragments, minor plagioclase, and detrital zircons yielding not only early Paleozoic to Precambrian ages of Gondwanan affinity but also late Paleozoic to early Mesozoic ages. These younger zircons are characterized by euhedral to subhedral shape, well-developed oscillatory zoning, and $\varepsilon_{\mathrm{Hf}}(t)$ values mostly between −3 and 4 corresponding to crustal mode ages ($T_{\mathrm{DM}}{}^{\mathrm{C}}$) of 1.5−1.0 Ga. Volcanic detritus and late Paleozoic-early Mesozoic zircon grains are lacking in the overlying Derirong Formation.

(3) Provenance signatures of Qulonggongba and Langjiexue sandstones are similar, indicating a common source of detritus and supporting the inference that the Langjiexue Group represents an *in situ* sedimentary unit rather than part of an exotic block.

(4) The Gondwanide orogen formed above the Pan-Pacific subduction zone along the southeastern margin of Gondwana represents the most plausible source for volcanic detritus including late Paleozoic-early Mesozoic zircons found in the Langjiexue Group and the Qulonggongba Formation. Sediments are inferred to have been transported by a transcontinental routing system analogous to the modern Amazon River in South America from the Gondwanide orogen to the Indian passive margin facing Neo-Tethys. Paleo-drainage patterns were influenced by rift-related penecontemporaneous regional uplift along the northern margin of eastern Gondwana.

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