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Discovery of Middle Jurassic trench deposits in the Bangong-Nujiang suture zone: implications for the timing of Lhasa-Qiangtang initial collision

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Abstract

The Mesozoic trench deposits in the Bangong-Nujiang suture zone in central Tibet can provide critical information for reconstructing the paleotectonic evolution of the Bangong-Nujiang Ocean and constraining the timing of the Lhasa-Qiangtang initial collision. In this paper, the Gamulong Formation, which is well exposed in the Dong Co area, western Bangong-Nujiang suture, central Tibet, was studied. The sedimentological analysis shows that the Gamulong Formation was deposited in a submarine fan environment. The youngest detrital zircon age and fossils from limestone pebbles within the Gamulong Formation combine to determine a Middle Jurassic age. The pebbles in the conglomerate are dominated by limestones and sandstones, which is consistent with the sandstone petrology showing limestone and sandstone fragments as the main framework components. Detrital zircon U-Pb ages from the sandstones yield age populations of 164-178 Ma, 200-500 Ma, 700-1000 Ma, 1700-2100 Ma and ~2500 Ma. The corresponding zircon $\varepsilon_{\text{Hf}}(t)$ values are distributed between -23.5 and +11.1. These zircon features are similar to those from the Qiangtang terrane. Accordingly, the provenance results imply that the Gamulong Formation was recycled from the accretionary complex (Mugangri Group mélangé) in the Bangong-Nujiang suture zone and the forearc basin deposits (Lower-Middle Jurassic

Sewa/Shaqiaomu/Jiebuqu formations) in the southern Qiangtang subterrane. The Gamulong Formation is characterized by sedimentary recycling in the trench, likely in response to a tectonic event (possibly the continental collision). Together with the previous studies, this work on the occurrence of the Gamulong Formation indicates that the Lhasa-Qiangtang initial collision could have occurred in Middle Jurassic time (~166 Ma).

Keywords: Provenance; Sedimentary recycling; Trench fills; Continental collision; Tibet

1 Introduction

The Bangong-Nujiang suture zone (BNSZ) lies in central Tibet and extends ~2000 km from the east to the west (Fig. 1a; Pan et al., 2012). It represents an important tectonic boundary separating the Lhasa and Qiangtang terranes and records the remnants of the Bangong-Nujiang Ocean during the Mesozoic time (Yin and Harrison, 2000; Pan et al., 2012). The evolution of the BNSZ is essential for understanding the early tectonic history of the Tibetan Plateau. Recently, studies from different disciplines have been conducted on this suture, such as structural geology (Kapp et al., 2003, 2005), petrology (Zhu et al., 2013, 2016; Fan et al., 2014), ophiolitic study (Shi, 2007; Wang et al., 2016) and sedimentary geology (Zhang et al., 2012; Huang et al., 2017; Li et al., 2017a, b); however, the time of Lhasa-Qiangtang initial collision remains under debate, ranging from the Middle Jurassic to Late Cretaceous time (Yin and Harrison, 2000; Kapp et al., 2005; Fan et al., 2014; Zhu et al., 2016; Ma et al., 2017). A Late Jurassic to Early Cretaceous collision has been widely accepted based on several lines of evidence, i.e., the ages of ophiolitic rocks in the BNSZ (Shi, 2007; Wang et al., 2016), nonmarine molasse deposits overlying marine deposition with an angular unconformity (Kapp et al., 2005) and the ~150-130 Ma magmatic gap in the southern Qiangtang subterrane (Zhu et al., 2016). Some researchers found the 132-108 Ma OIB-like basalts and related sedimentary rocks within the BNSZ and argued that the ocean was still open and that the collision could have occurred in the Late Cretaceous (Zhu et al., 2006; Fan

et al., 2014). Recently, Ma et al. (2017) found a set of ~166 Ma conglomerates above the marine limestones with an angular unconformity in the Shuanghu area (Fig. 1a); these deposits were interpreted as the Middle Jurassic Lhasa-Qiangtang collision. In addition, a diachronous collision along the BNSZ is acceptable, with collision propagating from the east to the west (Pan et al., 1983; Yin and Harrison, 2000; Yan et al., 2016).

The onset of a peripheral foreland basin on the underthrusting plate can be used to constrain the two continental initial collision (DeCelles et al 2014; Hu et al., 2017). As two continents collide, the accumulating zones between two continents (i.e., trench fills) are produced by the flexural subsidence in response to the contractional fold-thrust belt (corresponding to the foredeep depozone within the “foreland system”, DeCelles and Giles, 1996). The detritus from one continent is delivered to be deposited upon another continental landmass. Thus, the trench fills commonly record the detritus of initial approach, which implies the two continental initial collision (DeCelles et al 2014). According to this simple principle, lots of work has been conducted on the sedimentary rocks in the trench to constrain the continental initial collision. For instance, the “Sangdanlin section” in the Yarlung-Zangbo suture zone, southern Tibet, recorded the first arrival of the Asian detritus, which is used to precisely constrain the India-Asia initial collision (Ding et al., 2005; Wang et al., 2011; DeCelles et al 2014; Hu et al., 2015, 2017).

In the BNSZ of central Tibet, thick Mesozoic sedimentary rocks are well preserved (XZBGM, 1993; Zeng et al., 2006). Detrital zircon geochronology and provenance analysis from the Mesozoic strata in the BNSZ imply that the Late Triassic-Middle Jurassic Muganggri Group was formed in an accretionary complex, recording the accretion history in response to the northward subduction of the Bangong-Nujiang oceanic lithosphere (Zeng et al., 2015; Huang et al., 2017; Li et al., 2017a). The Lower-Middle Sewa, Shaqiaomu, and Jiebuqu formations in the southernmost Qiangtang terrane records shallow marine clastic and carbonate deposits derived from the magmatic arc in the southern Qiangtang subterrane, reflecting a forearc basin setting (Zeng et al., 2006; Huang et al., 2017; Ma et al., 2017). However, the absence of trench deposits in the BNSZ led to the interpretation of an incomplete subduction-collision system (Underwood and Moore, 1995). In this paper, the discovery of the Gamulong Formation exposed within the

Mugangangri Group is reported. Combining sedimentology, conglomerate composition, sandstone petrology, zircon U-Pb ages and Hf isotopes, the Gamulong Formation is interpreted as having been deposited in a submarine fan environment in the trench and mostly recycled from the previous sedimentary strata. Together with the paleotectonic settings, the finding of the Gamulong Formation improves the understanding of the Lhasa-Qiangtang initial collision along the BNSZ in the central Tibetan Plateau.

2 Geological setting

The BNSZ is a Mesozoic tectonic boundary in the central Tibetan Plateau, separating the Lhasa terrane to the south from the Qiangtang terrane to the north (Yin and Harrison, 2000). The geological components of these tectonic units are described as follows.

2.1 Lhasa terrane

The Lhasa terrane is commonly subdivided into two domains: the southern Lhasa subterrane and the northern Lhasa subterrane (Fig. 1a, Burg et al., 1983; England and Searle, 1986; Searle et al., 1987). The southern Lhasa subterrane is characterized by the Gangdese magmatic arc and Xigaze forearc basin. The Gangdese magmatic arc is mainly dominated by the Mesozoic-Cenozoic Gangdese batholiths and the coeval volcanic rocks including the Yeba Formation, the Sangri Group and the Linzizong volcanic rocks (Chu et al., 2006; Mo et al., 2007, 2008; Wen et al., 2008; Ji et al., 2009; Lee et al., 2009; Zhu et al., 2011a, 2015). In the southernmost Gangdese magmatic arc, the Xigaze forearc basin accumulated thick sequences of Albian-Campanian deep-water turbidites (Dürr, 1996; Wang and Liu, 1999; Wang et al., 2012; An et al., 2014; Orme et al., 2014, 2016) that were mainly sourced from the Gangdese magmatic arc (Wu et al., 2010; An et al., 2014). The northern Lhasa subterrane is composed of substantial Cretaceous magmatic rocks as well (i.e., Zenong volcanic rocks, Zhu et al., 2008, 2009, 2011a, Sun et al., 2015a). Very thick sedimentary successions of Carboniferous metasedimentary rocks, Permian limestones, Jurassic siliciclastic rocks and Cretaceous marine-terrestrial deposits are exposed in the northern Lhasa

subterranean (Leider et al., 1988; Yin et al., 1988; Zhang et al., 2004, 2011, 2012; Leier et al., 2007a, b; Sun et al., 2015b, 2017).

The pre-Jurassic detrital zircons from the Lhasa terrane tend to be in the age ranges of 150-200 Ma, 500-600 Ma and 1000-1300 Ma (Leier et al., 2007b; Gehrels et al., 2011; Zhu et al., 2011b). The zircon $\varepsilon_{Hf}(t)$ values are very positive in the southern Lhasa subterranean and mostly negative in the northern Lhasa subterranean (Zhu et al., 2011a and references therein).

2.2 BNSZ

The BNSZ is exposed ~2000 km along strike from the east to the west (Pan et al., 2004) and represents the remains of subduction of the Bangong-Nujiang oceanic lithosphere and the subsequent Lhasa-Qiangtang collision (Yin and Harrison, 2000; Kapp et al., 2005). It is commonly concluded that the closure of the Bangong-Nujiang ocean and the subsequent Lhasa-Qiangtang collision occurred during Late Jurassic-Early Cretaceous time (Kapp et al., 2007; Zhu et al., 2011a, 2016). Recently, a Late Cretaceous Lhasa-Qiangtang collision has been proposed by Fan et al. (2014) based on the subduction-related oceanic island model.

There are many suites of ophiolitic fragments scattered in the BNSZ. Geochronological studies reveal that these ophiolites formed between 190 and 160 Ma (i.e., Dengqen area, Liu et al., 2002; Wang et al., 2016; Dongqiao area, Shi et al., 2007, 2012; Wang et al., 2016; Gaize area, Qiu et al., 2004; Zeng et al., 2006; Bao et al., 2007; Wang et al., 2008; Wang et al., 2016; Rutog area, Shi et al., 2004, 2008; Wang et al., 2016). The Mesozoic Wuga Formation, Mugangri Group and Shamuluo Formation are preserved very well in the BNSZ, representing deep-water sedimentary environments (Zeng et al., 2015; Li et al., 2017a). The detrital zircons and the palaeontological fossils suggest that these formations were deposited during Late Triassic-Early Cretaceous time (Zeng et al., 2006; Li et al., 2017a, b).

The reported detrital zircons of the BNSZ are mostly from the Mugangri Group and yield age populations of 200-350 Ma, 400-700 Ma, 750-1000 Ma, 1750-1950 Ma and 2300-2500 Ma (Zeng et al., 2015; Huang et al., 2017; Li et al., 2017a). The corresponding $\varepsilon_{Hf}(t)$ values show a varied distribution, ranging from -23.5 to +11.1 (Huang et al., 2017; Li et al., 2017a).

2.3 Qiangtang terrane

The Qiangtang terrane can be divided into the southern and northern Qiangtang subterrane by the Longmu Co-Shuanghu suture zone (LSSZ) (Li et al., 1995), which is also characterized by the high-pressure Qiangtang metamorphic belt including blueschist, eclogite, ophiolitic mélangé and metasedimentary rocks (Zhang et al., 2007; Pullen et al., 2008; Zhai et al., 2011; Tang and Zhang, 2014). Magmatism from ~185-150 Ma and 130-100 Ma is well developed in the southern Qiangtang subterrane (Liu et al., 2017). The thick Lower-Middle Jurassic deposits crop out in the south margin of the southern Qiangtang subterrane and contain the Sewa Formation, Shaqiaomu Formation, and Jiebuqu Formation (Zeng et al., 2006; Huang et al., 2017). The Sewa Formation comprises marls, mudstone/shale, and limestone. The Shaqiaomu Formation is mainly composed of mudstone and sandstone interbedded with limestone. The Jiebuqu Formation consists of shallow marine limestone (Zeng et al., 2006). The northern Qiangtang subterrane features a sedimentary depression dominated by Triassic-Jurassic terrestrial-marine sedimentary-volcaniclastic rocks intercalated with volcanic rocks (Fu et al., 2008; Wang et al., 2008). Triassic magmatic activity has been recorded in the northern Qiangtang subterrane with zircon U-Pb ages of ~223-205 Ma (Zhai et al., 2013; Peng et al., 2015).

The detrital zircons from the Qiangtang terrane are characterized by age populations of 200-300 Ma, 500-650 Ma, 700-1000 Ma, 1800-2000 Ma, and ~2500 Ma (Leier et al., 2007b; Pullen et al., 2008, 2011; Dong et al., 2011; Gehrels et al., 2011; Zhu et al., 2011b). The Lower-Middle Jurassic Sewa Formation in the southernmost Qiangtang terrane (represented as the forearc deposits) yields zircon age populations of 210-300 Ma, 420-500 Ma, 780-850 Ma and 2400-2500 Ma, with the $\varepsilon_{\text{Hf}}(t)$ values ranging from -25 to +15 (Huang et al., 2017; Ma et al., 2017). In addition, the igneous zircons yield ages of 185-150 Ma and 130-100 Ma in the southern Qiangtang subterrane (Guynn et al., 2006; Li et al., 2014; Liu et al., 2014, 2017), 325-471 Ma in the central Qiangtang metamorphic belt (Pullen et al., 2008), and 205-223 Ma in the northern Qiangtang subterrane (Li et al., 2007; Wang et al., 2007; Zhai and Li, 2007; Zhai et al., 2013; Peng et al., 2015). The $\varepsilon_{\text{Hf}}(t)$ values from the detrital and igneous zircons of the Qiangtang terrane are

dispersed and vary from -25 to +11 (Yang et al., 2011; Zhai et al., 2013; Li et al., 2014; Liu et al., 2014, 2017; Hao et al., 2015; Peng et al., 2015).

2.4 The geology of the BNSZ in the Dong Co area

In the Dong Co area of this study, relatively complete ophiolite sequences are preserved, which have MORB- and OIB-like affinities with U-Pb ages of ~167 Ma and 132 Ma, respectively (Bao et al., 2007; Wang et al., 2016). In the north of these ophiolites, the Zhonggang OIB-like mafic rocks are well exposed (Fig. 1b). Zircon U-Pb dating shows that they have an Early Cretaceous age (~116 Ma, Fan et al., 2014). The formation of the Zhonggang OIB-like mafic rocks remains a matter of debate, concerning the ocean island model during subduction (Fan et al., 2014) or the decompression melting of the asthenosphere due to the break-off of the subducted Bangong-Nujiang oceanic slab (Zhu et al., 2016).

The sedimentary strata in the Dong Co area are the Muganggri Group and the Shamuluo Formation (Fig. 1b). The Muganggri Group displays fault contact with the Dong Co ophiolite and comprises several kilometres of strongly deformed deep-water turbidites with a large number of mélangé units (Zeng et al., 2015; Li et al., 2017a). However, in this study, it is found that the Muganggri Group have the obvious zonation, showing the massive mélanges ($J_{1-2} \text{ mlg}$) exposed east-west extension in the northern part of BNSZ, while the deep-water turbidites (normally graded stata, $J_{1-2} \text{ m}$) distributed in the southern part of the BNSZ. These two different lithologic units are separated by the Gaize-Dongco road in geography (Fig. 1b). The Shamuluo Formation is in fault contact with the ophiolite (Zeng et al., 2006) or shows an angular unconformity with the underlying Muganggri Group (Li et al., 2017a, b). In addition, the Lower Cretaceous Qushenla Formation is widely exposed along the suture zone, including basaltic to intermediate volcanic rocks intercalated with minor clastic rocks (Zeng et al., 2006; Chen et al., 2014).

3 Analytical methods

3.1 Conglomerate and sandstone petrography

In the field, the conglomerate compositions (clast types) were counted at 7 locations using a 10×10 cm grid and at least 100 clasts were in statistics per point. A total of 13 petrographic thin sections were point-counted using the Gazzi-Dickinson method (Ingersoll et al., 1984). At least 400 grains were counted per sample, and the data were plotted in the QFL and LmLvLs ternary diagrams (Dickinson, 1985; Garzanti et al., 2007).

3.2 Zircon U-Pb dating and Hf isotopes

Zircon U-Pb ages were obtained on a laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the State Key Laboratory for Mineral Deposits Research (MiDeR), Nanjing University (NJU), China. The detailed instrumental conditions and analysis procedures can be referred to Liu et al. (2013). The correction of the mass discrimination and elemental fractionation for the standard zircon is followed by the method of Jackson et al. (2004). The applied zircon ages are $^{206}\text{Pb}/^{238}\text{U}$ ages if grain ages < 1000 Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages if grains > 1000 Ma. The common Pb isotopic data were calculated by GLITTER 4.4 (Van Achterbergh et al., 2001), and common Pb correction was conducted following Andersen (2002). The zircon age probabilities were performed using Isoplot (version 2.49) (Ludwig, 2001).

Zircon Hf isotope analyses were analyzed on the same zircon grains with U-Pb ages and was conducted at MiDeR-NJU, China, via a Thermo Scientific Neptune Plus mass spectrometer (MC-ICP-MS) coupled to a New Wave UP193 nm laser ablation system. Zircons were ablated with a beam of 50 μm in diameter, an 8 Hz of laser repetition rate, and an energy of 10.9-11.0 J/cm². The results were collected 200 times in 1 minute per zircon grain. The details of the analysis conditions and procedures are following Wang et al. (2013). The calculation of the results was applied as $1.867 \times 10^{-11} \text{ a}^{-1}$ for the decay constant of ^{176}Lu (Soderlund et al., 2004). The calculation of $\varepsilon_{\text{Hf}}(t)$ and Hf model age (T_{DM}^{C}) was followed the methods of Bouvier et al. (2008) and Griffin et al. (2002), respectively.

4 Sedimentology

In the Dong Co area, a set of ~ 200-m-thick conglomerate-dominated clastic rocks were discovered and further investigated near Gamulong Village; these rocks had not been mapped on the geological maps (Zeng et al., 2006). This conglomerate extending ~10 km from east to west, is well bedded and in fault contact with the underlying mafic rocks (ophiolitic assemblage) and the overlying *mélange* of the Mugangangri Group (Fig. 2, Fig. 3a). Moreover, the section B is totally exposed in the *mélange* of the Mugangangri Group with the fault contact (Fig. 2). About ~30 km east of the study area (north of the Zhaxi Cobu Lake), the conglomerates expose as the big blocks in the *mélanges* of the Mugangangri Group, indicating they could be strongly deformed into the *mélanges* after the deposition. To distinguish this well bedded conglomerate from the Mugangangri Group and discuss the detailed depositional processes, this stratigraphic unit is named the “Gamulong Formation” for the discussion in the following.

In the study area, two sections were investigated in detail (Fig. 2). Section A is ~210 m thick and mostly composed of a varied sequence of gray conglomerates, sandstones and mudstones. Section B has lithology similar to that of Section A and crops out with a combined thickness of ~200 m. Three lithofacies assemblages are recognized, and sedimentary descriptions and environment interpretations are given below.

4.1 Lithofacies assemblage 1: Conglomerates with sandy matrix

Description: This lithofacies is characterized by massive gray conglomerates with a thickness of ~150 m (Fig. 3b), indicating the major components of the Gamulong Formation. The conglomerate beds are commonly wedge-shaped to lenticular and laterally discontinuous. The normally graded conglomerate beds are occasionally observed. A prominent feature of this lithofacies is that these conglomerates are mostly filled with the sandy matrix instead of the muddy matrix. Based on the supporting structure, the conglomerates include two types: clast-supported and matrix-supported (Fig. 3c, d). The clast-supported conglomerates comprise pebble- to cobble-sized clasts with minor coarse sandstone matrix. The clasts are poorly sorted, subrounded and display weakly horizontal stratification with occasionally A-axis imbricated clasts (Fig. 3e). The clast size in the long dimension is ~10 cm on average, with a maximum size

of ~40 cm. The base of each conglomerate bed commonly shows an abrupt contact or erosional boundary with the underlying rocks. The individual conglomerate beds are unstable and discontinuous laterally with lengths of no more than 10 m. The vertical sequence of conglomerates shows disorganized and no significantly cyclic. The matrix-supported conglomerates have pebble- to boulder-sized angular clasts that are poorly sorted and usually disorganized. Scoured bases are very common in this lithofacies, showing the erosional surfaces. The matrix is composed of coarse-grained sandstones. The maximum clast size can be more than 50 cm (~10-20 cm on average). In addition to these conglomerate beds, some lenticular or wedge-shaped pebbly coarse-grained sandstones are interbedded (Fig. 3f). The thicknesses of the sandstone beds are commonly within 10-50 cm. Planar horizontal lamination is occasionally observed in the sandstones.

Interpretation: The conglomerates of this lithofacies with poorly grading and clast disorganization are interpreted as the products of rapid sedimentation under an active, high-energy, concentrated and sediment-rich depositional system (Davies and Walker, 1974; Winn and Dott, 1979). The clast-supported conglomerates represent high density sandy and/or grain flow with non-cohesive (lack of the mud-matrix), while the matrix-supported conglomerates represent high density debris currents from the suspension sedimentation (Lowe, 1979; Naylor, 1980; Blair and McPherson, 1994). Given the lithofacies association described in the following section of this study, an inner channelled region of coarse-grained submarine fan is a reasonable environment for interpretation of these massive conglomerates (Ineson, 1989).

4.2 Lithofacies assemblage 2: Pebbly graded sandstones

Description: This lithofacies assemblage features coarse- to very coarse-grained sandstones, and some are pebbly. This lithofacies is typically intercalated with lithofacies 1 (Fig. 2). These pebbly sandstones are very common in the outcrops and well developed in both sections with thicknesses of ~1-2 m (commonly 0.5-1.5 m thick, Fig. 3g) per sandstone package, which fill the most shallow scours. The bases of these sandstone packets commonly show discontinuities within a few meters (no more than 10 m) and are interdigitated by the other coarser or finer-grained

lithofacies. Every single pebbly sandstone bed has a scoured base and an abrupt boundary with the underlying beds. From the bottom to the top, the sandstone package shows upward fining with the thick-bedded and graded-stratified pebbly sandstones at the base. The pebbles in the lower part of the sandstone package are mostly scoured from the underlying beds and are ~1-2 cm in size. Above the pebbly sandstones, stratified sandstone beds are well developed and mottled with thickness of ~0.5-2 m. Slightly normal grading and parallel laminations are common. The cross-laminated beddings are rare in these graded-stratified sandstones.

Interpretation: This lithofacies is interpreted as representing deposition from highly concentrated sandy turbidity currents, largely out of high-density suspensions. The stratified sandstone beds indicate a phase of tractional deposition during the waning of the current (Ineson, 1989). This lithofacies assemblage of pebbly sandstones and graded sandstones indicates a relatively episodic nature of high-energy environment with the channel system. Therefore, combining these depositional features and above, the braided channel and the channel levee deposits within a submarine fan provide a possible interpretation (Mutti, 1977; Mutti and Ricci Lucchi, 1978).

4.3 Lithofacies assemblage 3: Mudstones interbedded with sandstones

Description: This lithofacies is mainly developed in Section A with a thickness of ~50 m in total. The mudstone beds in this lithofacies are always mottled and slightly thicker (~10-50 cm) than the intercalated sandstone beds (usually no more than 10 cm-thick). The compositions show clays and very fine siltstones intercalated. The tops of the mudstones usually have erosive boundaries with rarely continuous laterally (~5-10 m, Fig. 3h). Normal grading and occasional parallel laminations appear in the mudstones. These mudstone beds are commonly interbedded with medium- and fine-grained thin sandstone beds (some are pebbly). The individual sandstone beds are commonly ~5-10 cm in thick and have sharp basal contacts with the underlying mudstones. The parallel laminations and small-scale cross-laminations are developed in the medium-grained sandstones. In addition, there are occasionally exposed the isolated lenticular, scoured conglomerates and intraformational slid blocks in the mudstone lithofacies.

Interpretation: The mudstones are consistent with deposits of diluted low-concentration turbidity currents with suspension fallout (Mutti and Ricci Lucchi, 1978). The interbedded thin graded sandstone beds are interpreted to have been deposited under low-density turbidity currents, resulted from the more extensive channel breaching (Ineson, 1989). The intraformational blocks are emplaced by sliding. Integrating this lithofacies assemblage, it represents a relatively low-energy environment, which accumulated the sediments mainly from the overbank deposits of turbidity currents. The channel levee and crevasse splay within submarine fan can be considered as this sedimentary environment (Mutti, 1977; Ineson, 1989).

5 Analytical results

5.1 Conglomerate clast counts and lithology

Approximately 700 conglomerate clasts were counted at 7 sites in sections A and B (Fig. 2). The lithological components of the clasts are sandstones, limestones, and minor volcanic rocks. The sandstones comprise ~56.9% of the total clasts on average and are mostly sedimentary litharenites (Fig. 4a). Quartz-rich sandstones are very common as well. Limestones account for ~42.7% of the total clasts and consist mostly of microcrystalline limestone with some recrystallized corals and algae (Fig. 4b, e, and f). The rest of the clasts are a few volcanic rocks that represent a minor proportion only and are mostly intermediate to felsic rocks.

5.2 Sandstone modal composition

A total of 13 sandstones from the Gamulong Formation are mostly poorly sorted, include siliceous or calcareous cements and feature angular to subrounded grains. These sandstones have average modal compositions of Q:F:L = 35:11:54 (see Appendix table 1, Fig. 5). Among these compositions, the sedimentary fragments (limestones and clastic rocks, Fig. 4c) are the primary components composing ~53.3% of the total framework grains. Monocrystalline quartz is the secondary component and consists of ~34.1% of the total framework grains, while polycrystalline quartz is rare. The quartz grains are commonly subrounded to rounded (Fig. 4d). The K-feldspar

grains are the main feldspar components and comprise ~6.6% of the total grains. Zircon, muscovite and magnetite are common accessory minerals. In the QFL and LmLvLs modal composition discrimination diagrams (Fig. 5, Dickinson, 1985; Garzanti et al., 2007), all the sandstones plot in the field of “recycled orogeny”, featuring recycled source areas.

5.3 Zircon U-Pb ages and Hf isotopes

A total of 255 detrital zircons from three sandstones of the Gamulong Formation (sample locations shown in the sedimentary logs of Fig. 2) were analysed for U-Pb ages. The measured zircon U-Pb ages are shown in Appendix table 2 and Fig. 6. In particular, the available 90 zircons from sample 16GM12 (Section B) of a sandstone pebble yield a Mesozoic age population of 200-350 Ma (peaking at ~270 Ma) with the youngest age of 203 ± 3 Ma. However, 83 of 90 zircons have pre-Mesozoic ages with age ranges of 410-450 Ma, 700-1000 Ma, 1700-2000 Ma and ~2500 Ma. The 75 zircons from sample 16GM19 (Section B) from the sandstone matrix of the Gamulong Formation produce age populations of 170-176 Ma (the youngest ages are 170 ± 3 Ma, 173 ± 3 Ma, and 176 ± 3 Ma), 210-280 Ma, 400-450 Ma, 515-610 Ma, 1800-2100 Ma, and 2400-2550 Ma. Among these 75 zircons, the pre-Mesozoic zircons account for nearly 83%. Of the 90 zircons in sample 17YL01 from the sandstone matrix (Section A), 13 zircons exhibit young age populations of 164-178 Ma and 210-280 Ma with the youngest age of 164 ± 3 Ma. The other 77 zircons yield age distributions of 400-500 Ma, 700-900 Ma, 1800-2000 Ma, and 2400-2550 Ma.

A total of 69 detrital zircon Hf isotopic analyses were conducted on the same individual zircons that provided the U-Pb ages (Appendix table 3; Fig. 7). The results yield varied $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic ratios ranging from 0.282911 to 0.283128. The corresponding $\epsilon_{\text{Hf}}(t)$ values are distributed between -23.5 and +11.1 (average of -4.5) with T_{DM}^{C} model ages of 2.8-0.6 Ga.

6 Discussion

6.1 Depositional age of the Gamulong Formation

Previous studies by the geological survey have placed the Gamulong Formation in the Mugagangri Group and give an approximate Jurassic age based on the corals from the sedimentary matrix (Zeng et al. 2006; Cao et al. 2008). The youngest detrital zircons from the Mugagangri Group yield ages of Late Triassic to Middle Jurassic (continuing at least to late Middle Jurassic time, ~163 Ma, Huang et al., 2017; Li et al., 2017a). In this study, the limestone pebbles from the Gamulong Formation yield *Andersenolina elongata* and *Neotrocholina* sp., showing ages of Middle Jurassic-Early Cretaceous (Bathonian-Aptian, Fig. 4e, f). The youngest detrital zircons commonly provide the maximal depositional age for the sedimentary strata, which has been proved effectively in sandstones from the Colorado Plateau (Dickinson and Gehrels, 2009). In this study, the age constraint for the Gamulong Formation is best determined by the youngest detrital zircons from the sandstone matrix, which can be closer to the true depositional age. Samples 17YL01 and 16GM19 of the sandstone matrix from the Gamulong Formation yield the youngest detrital zircon age populations ranging between 164 Ma and 178 Ma with the youngest detrital zircon $YC1\sigma(2+)$ age of 166 ± 2 Ma (the detrital zircon $YC1\sigma(2+)$ age is a reliable way of determining the age of depositional strata, and the calculation method can be found in Dickinson and Gehrels, 2009). Therefore, in consideration of the Middle Jurassic-Early Cretaceous limestone pebbles, it can be concluded that the Gamulong Formation was being deposited until ~166 Ma at least. According to the rapid depositional features of the Gamulong Formation, the youngest detrital zircon age of ~166 Ma can approximately represent the sedimentary age in this work. In addition, the source strata of the accretionary complex and forearc deposits (see the discussion in section 6.2 below) might have continued to accumulate to approximately Middle Jurassic time (i.e., ~163 Ma, Zeng et al., 2006; Huang et al., 2017; Li et al., 2017a; Ma et al., 2017), which also supports a Middle Jurassic age for the deposition of the Gamulong Formation.

6.2 Provenance analysis and sedimentary recycling

The detrital zircons from two sandstone matrices and one sandstone pebble of the Gamulong Formation yield similar age spectra (Fig. 6), showing age populations of 164-178 Ma, 200-500 Ma, 700-1000 Ma, 1700-2100 Ma and ~2500 Ma. Comparing these age signatures with the above potential sources, they are quite similar to the detrital and igneous zircons from the Qiangtang

terrane to the north, featuring as the age populations of ~200-500 Ma, 700-1000 Ma, 1800-2000 Ma and ~2500 Ma (Fig. 8), and distinct from the Lhasa terrane to the south, with the age ranges of 500-600 Ma (peaking at ~550 Ma) and 1000-1300 Ma (peaking at ~1170 Ma) (Fig. 8, Gehrels et al., 2011; Leier et al., 2007b; Zhu et al., 2011b). In particular, the youngest 164-178 Ma zircons were likely from the 150-185 Ma magmatic rocks exposed in the southern Qiangtang terrane. The scattered zircon $\varepsilon_{Hf}(t)$ values of the Gamulong Formation are consistent with the Qiangtang terrane as well (Fig. 7), which also supports the Qiangtang affinity provenance features.

The abundant sedimentary clasts (limestone and sandstone pebbles) in the conglomerate beds of the Gamulong Formation suggest that they are not likely derived from the Qiangtang terrane directly because of the broad magmatism that developed in the Qiangtang terrane during Mesozoic time (Guynn et al., 2006; Li et al., 2007; Wang et al., 2007b; Zhai and Li, 2007; Pullen et al., 2008; Zhai et al., 2013; Li et al., 2014; Liu et al., 2014, 2017; Peng et al., 2015). The sedimentary characteristics of the Gamulong Formation imply they were deposited from local sources in a submarine fan environment. The detrital zircons of the BNSZ are confirmed to be derived from the Qiangtang terrane as they show similar zircon signatures (Fig. 8, Zeng et al., 2015; Huang et al., 2017; Li et al., 2017a). Hence, whether the Gamulong Formation was derived directly from the Qiangtang terrane or recycled from the BNSZ and/or the Qiangtang terrane needs further investigation. It is known that the arc magmatism (mostly intrusive rocks) was extensively developed in the southern Qiangtang subterrane during 185-150 Ma (Guynn et al., 2006; Li et al., 2014; Liu et al., 2014, 2017). In this case, these intrusive rocks have not been denudated and eroded directly for the simultaneous Gamulong Formation, which is supported by the few 185-150 Ma zircons (there are only 10 out of 255 zircons in total ranging between 164 Ma and 178 Ma) existed in the Gamulong Formation. The sandstone petrological results show that there are abundant sedimentary rock fragments (limestones and sandstones) instead of volcanic rock fragments (Fig. 4a, b). In the QFL and LmLvLs diagrams (Fig. 5), all samples plot in the area of recycled orogeny. The conglomerate clasts indicate the same detrital components, showing limestone and sandstone pebbles as the majority (Fig. 2). Both the rock fragments in sandstones and the pebbles in conglomerates yield abundant sedimentary clasts, showing the recycling feature

of the provenance. The sedimentary analysis indicates a submarine fan environment in which the deposits are commonly transported rapidly and derived from local sources (Ineson, 1989). Therefore, the Gamulong Formation could be recycled from the previous sedimentary strata nearby. Combining this information with the geological background in the study area, the Late Triassic-Middle Jurassic accretionary complex (Mugagangri Group) in the BNSZ and the Lower-Middle Jurassic forearc deposits (i.e., Sewa Formation, Shaqiaomu Formation and Jiebuqu Formation, Zeng et al., 2006) in the southern Qiangtang subterrane are possible sources. The high similarities of the zircon U-Pb ages and Hf isotopes among the Gamulong Formation, Mugagangri Group and Sewa Formation (Fig. 7, 8) support this provenance interpretation. In addition, the age constraints of limestone pebbles from the Gamulong Formation are consistent with this interpretation.

6.3 Tectonic models and implications for the Lhasa-Qiangtang initial collision

The Mesozoic sedimentary deposits in the BNSZ and the southernmost Qiangtang terrane record the subduction of the Bangong-Nujiang oceanic crust and the subsequent collisional processes between the Lhasa and Qiangtang terranes. Any depositional model for the Gamulong Formation should account for the following factors: a) the Gamulong Formation is exposed in the mélangé of the Mugagangri Group with the fault contact; b) the spatial locations of the Gamulong Formation and the Mugagangri Group mélangé (accretionary complex) in the BNSZ, imply the southernmost margin of the Qiangtang terrane; c) the sedimentological analysis reveals the Gamulong Formation has been deposited in a submarine fan environment; and d) abundant sedimentary clasts (sandstone and limestone) in the Gamulong Formation indicate that they were mostly derived from the previous sedimentary strata, probably the forearc basin deposits in the southern Qiangtang terrane and the accretionary complex in the BNSZ.

In our study area, it is difficult to investigate the base of the Gamulong Formation because of the limited outcrops. However, as outlined above, a trench model has been proposed for interpreting the depositional processes of the Gamulong Formation. Under this model, the Gamulong Formation would represent the trench deposits in the front of the accretionary complex

(Mugangri Group mélange). All the depositional materials were recycled from the accretionary complex and the forearc deposits in the southernmost Qiangtang terrane. However, in consideration of the geological backgrounds, two contrasting tectonic models could be likely proposed for interpreting the tectonic evolution of the Gamulong Formation.

6.3.1 Model 1: Trench deposits under oceanic subduction

In Middle Jurassic time, with the continued northward subduction of the Bangong-Nujiang oceanic lithosphere, in the southernmost Qiangtang terrane, the Middle Jurassic Sewa, Shaqiaomu, and Jiebuqu formations were deposited with clastic rocks and limestones in a shallow marine environment in the forearc basin, with the detrital source derived from the Qiangtang terrane to the north (Huang et al., 2017; Ma et al., 2017). At the same time, the Mugangri Group continued to develop and was characterized by the sandy and ophiolitic mélange (Zeng et al., 2006). It is convincing that the Mugangri Group mélange formed within the accretionary complex in response to the subduction (to collision?) of the Bangong-Nujiang oceanic lithosphere (Zeng et al., 2015; Li et al., 2017a). There are many Jurassic zircons observed in the deposits from the above accretionary complex and forearc basin (Huang et al., 2017; Li et al., 2017a), which implies that the 185-150 Ma magmatic rocks in the southern Qiangtang subterrane were their main sources (Guynn et al., 2006; Li et al., 2014; Liu et al., 2014, 2017). Under this tectonic framework at the time, the Gamulong Formation was deposited in the trench in front of the accretionary complex, which formed a trench-arc system in response to the northward subduction of the Bangong-Nujiang oceanic lithosphere (Fig. 9a). However, under this model, it is difficult to interpret the abundant sedimentary clasts eroded from the accretionary complex and forearc basin because the accretionary complex and the forearc basin are generally in the accumulating domain instead of the erosional region during subduction processes. For instance, the Xigaze forearc basin in the southern Lhasa terrane, continuously subsided and accumulated thousands of metres of deposits during Cretaceous time with the subduction of the Neo-Tethyan oceanic lithosphere (Dürr, 1996; Wang et al., 2012; An et al., 2014). The sedimentary records and low-temperature thermochronology reveal that the Xigaze forearc basin has been uplifted and eroded until the Paleocene-Eocene time after the India-Asia collision (Wang et al., 2015; Li et al., 2017). A

possibility is that a tectonic event (such as the Lhasa-Qiangtang initial collision) had occurred in the BNSZ and an axial (or lateral) transport system existed in the trench, which delivered the neighbouring accretionary complex and the forearc deposits for the Gamulong Formation. An axial transport system is very common in the trench during subduction (Underwood and Moore, 1995), such as the modern Chile Trench, in which the axial transport system can develop for several hundreds of kilometres (Schweller et al., 1981; Thornburg et al., 1990). The sedimentation in the Nima-Shuanghu area (east of the study area, see Fig. 1a), recorded a major tectonic event with intense folding and thrusting in Middle Jurassic time (166 ± 1 Ma). Ma et al. (2017) interpreted this event as the collision between the Lhasa and Qiangtang terranes, which is consistent with our study. Under this tectonic model, the eroded materials from the accretionary complex and the forearc basin in the collision zone were transported by the axial delivery system to the study area. This tectonic model implies that the Lhasa-Qiangtang collision should be diachronous along the BNSZ. The collision could have occurred earlier in the east and then propagated to the west (Pan et al., 1983; Yin and Harrison, 2000; Yan et al., 2016).

6.3.2 Model 2: Trench deposits in response to the Lhasa-Qiangtang continental collision

The Gamulong Formation of this study is mainly composed of the cobble- to boulder-sized conglomerate that was recycled from the accretionary complex and the forearc basin. An alternative possibility is that the initial collision between the Lhasa and Qiangtang terranes was occurring during the deposition of the Gamulong Formation (i.e., ~166 Ma, Fig. 9b). In particular, the Gamulong Formation is located south of the ophiolitic rocks in the BNSZ (Fig. 1b), indicating this formation could have originally formed in the northernmost margin of the Lhasa terrane. The sedimentological analysis reveals that these rocks were deposited in a deep-sea environment (i.e., trench deposits). Commonly, deep-sea deposits on the distal margin of the underplate record the transition from continental rise to trench sedimentation during the initial continental collision (Hu et al., 2015, 2017). For example, the deep-sea turbidites in the northern distal Indian margin (Sangdanlin Section) record an obvious provenance change from India-affinity to Asia-affinity detritus and provide an older minimum age for the onset of the India-Asia collision (Ding et al., 2005; Wang et al., 2011; DeCelles et al. 2014; Hu et al., 2015, 2017). However, the deep-sea

deposits in the trench are generally preserved with difficulty because of the significant collisional deformation afterward (Hu et al., 2017). In the Yarlung-Zangbo suture zone, only one Sangdanlin Section was reported along such a ~1200 km suture zone from east to west. The Gamulong Formation of this study records Qiangtang-affinity detritus only, which can indicate the initial Lhasa-Qiangtang collision, even though the Lhasa-affinity strata are missing in this section. Under this tectonic model, the onset of initial collision resulted in the uplift and erosion of the accretionary complex and the forearc basin. Abundant sedimentary clasts were eroded and transported by the submarine canyon to the trench. With this model, it is easy to interpret the substantial sedimentary recycling of the Gamulong Formation. With the progression of the collision, the deformation and progradation of the accretionary complex developed southward, thereby resulting in the Gamulong Formation being exposed in the Mugangri Group *mélange*. This phenomenon is quite common in suture zones, such as the trench deposits of the Luogangcuo Formation (An et al., 2018) and the deep-sea turbidites in the Sangdanlin Section (Ding et al., 2005; Wang et al., 2011; DeCelles et al 2014; Hu et al., 2015, 2017) exposed in the Xiukang *mélange*, Yarlung-Zangbo suture zone, southern Tibet, which was the subduction-related accretionary complex in response to the subduction of the Neo-Tethyan oceanic crust.

This Middle Jurassic Lhasa-Qiangtang initial collision time is coincident with that from a study in the southern Qiangtang basin in the Shuanghu area (Ma et al., 2017). Given these studies, it can be concluded that the Lhasa-Qiangtang initial collision occurred in Middle Jurassic time (~166 Ma) from Nima to Gaize along the BNSZ. As stated in the introduction, the development of a collision-related peripheral foreland basin on the underlying plate is widely used to constrain an initial continental collision, such as the Paleocene peripheral foreland basin in response to India-Asia collision along the Yarlung-Zangbo suture in southern Tibet (Ding et al., 2005, 2009; Hu et al., 2012, 2016, 2017; DeCelles et al 2014). Within the foreland model (DeCelles and Giles, 1996), the Gamulong Formation in the trench could be likely the first record of the foredeep deposits in a peripheral foreland basin system. Recently, Li et al. (2017b) found that the Late Jurassic-Early Cretaceous Wuga Formation south of this study area was deposited in a peripheral foreland basin resulting from the Lhasa-Qiangtang collision. In the northern Lhasa subterranean, a

peripheral foreland basin has been defined based on sedimentological and provenance analysis during the Early Cretaceous (Leeder et al., 1988; Zhang et al., 2004; Kapp et al., 2007; Leier et al., 2007a). According to these findings and those from the Gamulong Formation of this study, the initial time of the collision-related peripheral foreland basin is shown to become younger from the BNSZ to the northern Lhasa subterrane. This relation could imply that foreland fold-thrust belts were propagating from the BNSZ in the Middle Jurassic to the northern Lhasa subterrane in the Late Jurassic-Early Cretaceous (Kapp et al., 2007), which is consistent with the deformation and migration of the foreland basin during the ongoing collision (DeCelles and Giles, 1996).

7 Conclusions

The new findings from the Gamulong Formation exposed within the Muganggri Group in the Dong Co area, western BNSZ, central Tibet, give additional information to constrain the onset of the Lhasa-Qiangtang initial collision.

- 1) The Gamulong Formation is composed mostly of thick conglomerate beds intercalated with some very coarse-grained or pebbly sandstones. These conglomerates were deposited in a submarine fan environment during Middle Jurassic time (~166 Ma).
- 2) The provenance results imply that the Gamulong Formation was mostly recycled from previous sedimentary strata. The accretionary complex (Muganggri Group *mélange*) in the BNSZ and the forearc deposits (Lower-Middle Jurassic Sewa/Shaqiaomu/Jiebuqu formations) in the southern Qiangtang subterrane are the likely sources.
- 3) The sedimentary recycling of the Gamulong Formation, together with the coeval deposition in the BNSZ and the southern Qiangtang subterrane, implies that the initial Lhasa-Qiangtang collision could have occurred during the Middle Jurassic time (~166 Ma).

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References

- An, W., Hu, X.M., Garzanti, E., 2018. Discovery of Upper Cretaceous Neo-Tethyan trench deposits in south Tibet (Luogangcuo Formation). *Lithosphere* doi: 10.1130/L690.1.
- An, W., Hu, X., Garzanti, E., Marcelle, M.K., Wang, J., and Sun, G., 2014. Xigaze Forearc Basin (South Tibet) revisited: Unroofing of the Gangdese arc and origin of the Xigaze ophiolite. *Geological Society of America Bulletin* 126, 1595–1613.
- Andersen, T., 2002. Correction of common lead in U–Pb analyses that do not report ^{204}Pb . *Chemical Geology* 192, 59–79.
- Bao, P.S., Xiao, X.C., Su, L., Wang, J., 2007. Petrological, geochemical and chronological constraints for the tectonic setting of the Dongco ophiolite in Tibet. *Science in China Series D: Earth Sciences* 50, 660–671 (in Chinese with English abstract).
- Blair, T.C., and McPherson, J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research* 64, 450–489.
- Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters* 273, 48–57.
- Burg, J.P., Proust, F., Tapponnier, P., and Chen, G.M., 1983. Deformation phases and tectonic evolution of the Lhasa block, China. *Eclogae Geologicae Helvetiae* 76, 643–665.
- Cao, S., Xiao, X., Ouyang, K., 2008. Re–new–establishment of the Jurassic Muganggri groups and its geological significance on the western side of the Bangong Co–Nujiang junction zone. *Acta Sedimentologica Sinica* 26, 559–564 (in Chinese with English abstract).

- Chen, Y., Zhu, D.C., Zhao, Z.D., Meng, F.Y., Wang, Q., Santosh, M., Wang, L.Q., Dong, G.C., Mo, X.X., 2014. Slab breakoff triggered ca. 113 Ma magmatism around Xainza area of the Lhasa Terrane, Tibet. *Gondwana Research*, 26, 449–463.
- Chu, M., Chung, S., Song, B., Liu, D., O'Reilly, S., Pearson, N., Ji, J., Wen, D., 2006. Zircon U–Pb and Hf Isotope Constraints on the Mesozoic Tectonics and Crustal Evolution of Southern Tibet. *Geology* 34, 745–748.
- Davies, J.C., and Walker, R.G., 1974. Transport and deposition of resedimented conglomerates: the Cap Enrag Formation, Cambro–Ordovician, Gaspt, Quebec. *Journal of Sedimentary Research* 44, 1200–1216.
- DeCelles, P.G., and Giles, K.A., 1996. Foreland basin systems. *Basin Research* 8: 105–123.
- DeCelles, P.G., Kapp, P., Gehrels, G.E., Ding L., 2014. Paleocene–Eocene foreland basin evolution in the Himalaya of southern Tibet and Nepal: Implications for the age of initial India–Asia collision. *Tectonics* 33:824–849.
- Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), *Provenance of arenites*. NATO Advanced Studies Institute Series 148, pp. 333–361.
- Dickinson, W., and Gehrels, G., 2009. Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database. *Earth and Planetary Science Letters* 288, 115–125.
- Ding, L., Kapp, P., Wan, X.Q., 2005. Paleocene–Eocene record of ophiolite obduction and initial India–Asia collision, south central Tibet. *Tectonics* 24: TC3001.
- Ding, L., Cai, F.L., Zhang, Q.H., Zhang, L.Y., Xu, Q., Yang, D., Liu, D.L., Zhong, D.L., 2009. Provenance and tectonic evolution of the foreland basin system in Gandese–Himalayan collisional orogen belt. *Chinese Journal of Geology* 44: 1289–1311 (in Chinese with English abstract).

- Dong, C., Li, C., Wan, Y., Wang, W., Wu, Y., Xie, H., Liu, D., 2011. Detrital zircon age model of Ordovician Wenquan quartzite south of Longmuco–Shuanghu Suture in the Qiangtang area, Tibet: constraint on tectonic affinity and source regions. *Science China Earth Science* 54, 1034–1042.
- Dürr, S.B., 1996. Provenance of Xigaze forearc clastic rocks (Cretaceous, south Tibet). *Geological Society of America Bulletin* 108, 669–691.
- England, P., and Searle, M., 1986. The Cretaceous–Tertiary deformation of the Lhasa block and its implications for crustal thickening in Tibet. *Tectonics* 5, 1–14.
- Fan, J.J., Li, C., Xie, C.M., Wang, M., 2014. Petrology, geochemistry, and geochronology of the Zhonggang ocean island, northern Tibet: implications for the evolution of the Banggongco–Nujiang oceanic arm of the Neo–Tethys. *International Geology Review* 56, 1504–1520.
- Fu, X.J., Wang, J., Wang, Z.J., Chen, W.X., 2008. U–Pb age and geochemical characteristics of volcanic rocks from the Juhua Mountain area in the northern Qiangtang Basin, northern Xizang (Tibet). *Geological Review* 54, 232–243 (in Chinese with English abstract).
- Garzanti, E., Doglioni, C., Vezzoli, G., Ando, S., 2007. Orogenic belts and orogenic sediment provenance. *The Journal of Geology* 115, 315–334.
- Gehrels, G., Kapp, P., DeCelles, P., Pullen, A., Blakey, R., Weislogel, A., Ding, L., Guynn, J., Martin, A., McQuarrie, N., Yin, A., 2011. Detrital zircon geochronology of pre–Tertiary strata in the Tibetan–Himalayan orogen. *Tectonics* 30, TC5016, doi:10.1029/2011TC002868.
- Griffin, W.L., Wang, X., Jackson, S.E., Pearson, N.J., O'Reilly, S.Y., Xu, X.S., Zhou, X.M., 2002. Zircon chemistry and magma mixing, SE China: in–situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* 61, 237–269.

- Guynn, J.H., Kapp, P., Pullen, A., Heizler, M., Gehrels, G., Ding, L., 2006. Tibetan basement rocks near Amdo reveal “missing” Mesozoic tectonism along the Bangong suture, central Tibet. *Geology* 34, 505–508.
- Hao, L.L., Wang, Q., Derek, D.A., Ou, Q., Dan, W., Jiang, Z.Q., Wu, F.Y., Yang, J.H., Long, X.P., Li, J., 2015. Underplating of basaltic magmas and crustal growth in a continental arc: Evidence from Late Mesozoic intermediate–felsic intrusive rocks in southern Qiangtang, central Tibet. *Lithos* 245, 223–242.
- Hu, X.M., Sinclair, H.D., Wang, J.G., Jiang, H.H., Wu, F.Y., 2012. Late Cretaceous–Palaeogene stratigraphic and basin evolution in the Zhepure Mountain of southern Tibet: Implications for the timing of India–Asia initial collision. *Basin Research* 24: 520–543.
- Hu, X.M., Garzanti, E., Moore, T., Raff, I., 2015. Direct stratigraphic dating of India–Asia collision onset at the Selandian (middle Paleocene, 59 ± 1 Ma). *Geology* 43, 859–86
- Hu, X.M., Wang, J.G., BouDagher-Fadel, M., Garzanti, E., An, W., 2016. New insights into the timing of the India–Asia collision from the Paleogene Quxia and Jialazi formations of the Xigaze forearc basin, South Tibet. *Gondwana Research* 32: 76–92.
- Hu, X.M., Wang, J.G., An, W., Garzanti, E., Li, J., 2017. Constraining the timing of the India–Asia continental collision by the sedimentary record. *Science China Earth Sciences* 60(4): 603–625.
- Huang, T.T., Xu, J.F., Chen, J.L., Wu, J.B., Zeng, Y.C., 2017. Sedimentary record of Jurassic northward subduction of the Bangong–Nujiang Ocean: insights from detrital zircons. *International Geology Review* 59, 166–184.
- Ineson, J.R., 1989. Coarse–grained submarine fan and slope apron deposits in a Cretaceous back–arc basin, Antarctica. *Sedimentology* 36, 793–819.

- Ingersoll, R.V., Bullard, T.F., Ford, R.L., Grimm, J.P., Pickle J.D., Sares, S.W., 1984. The effect of grain size on detrital modes: A test of the Gazi–Dickinson pointcounting method. *Journal of Sedimentary Petrology* 54, 103–116.
- Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousoval, E.A., 2004. The application of laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) to in situ U/Pb zircon geochronology. *Chemical Geology* 211, 47–69.
- Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. Zircon U–Pb Geochronology and Hf Isotopic Constraints on Petrogenesis of the Gangdese Batholith, Southern Tibet. *Chemical Geology* 262, 229–245.
- Kapp, P., Decelles, P. G., Gehrels, G. E., Heizler, M., Ding, L., 2007. Geological records of the Lhasa–Qiangtang and Indo–Asian collisions in the Nima area of Central Tibet. *Geological Society of America Bulletin* 119, 917–932.
- Kapp, P., Murphy, M.A., Yin, A., Harrison, T.M., Ding, L., Guo, J., 2003. Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet. *Tectonics* 22, 1029 doi: 10.1029/2001TC001332.
- Kapp, P., Yin, A., Harrison, T.M., Ding, L., 2005. Cretaceous–Tertiary shortening, basin development, and volcanism in central Tibet. *Geological Society of America Bulletin* 117, 865–878.
- Lee, H.Y., Chung, S.L., Lo, C.H., Ji, J.Q., Lee, T.Y., Qian, Q., Zhang, Q., 2009. Eocene Neotethyan slab breakoff in southern Tibet inferred from the Linzizong volcanic record. *Tectonophysics* 477, 20–35.
- Leeder, M.R., Smith, A.B., and Jixiang, Y., 1988. Sedimentology and paleoenvironmental evolution of the 1985 Lhasa to Golmud Geotraverse. *Philosophical Transactions of the Royal Society of London, series A* 327, 107–143.

- Leier, A. L., Decelles, P. G., Kapp, P., and Gehrels, G. E., 2007a. Lower Cretaceous strata in the Lhasa Terrane, Tibet, with implications for understanding the early tectonic history of the Tibetan Plateau. *Journal of Sedimentary Research* 77, 809–825.
- Leier, A.L., DeCelles, P.G., Kapp, P., Gehrels, G.E., Ding, L., 2007b. Detrital zircon geochronology of Phanerozoic sedimentary strata in the Lhasa terrane and implications for the tectonic evolution of southern Tibet. *Basin Research* 19, 361–378.
- Li, C., Cheng, L., Hu, K., Yang, Z., Hong, Y., 1995. Study on the Paleo–Tethys Suture Zone of Lungmu Co–Shuanghu. Tibet. Geological Publishing House, Beijing, China (in Chinese with English abstract).
- Li, C., Zhai, Q., Chen, W., Dong, Y., Yu, J., 2007. Geochronology evidence of the closure of Longmu Co–Shuanghu suture, Qinghai–Tibet Plateau: Ar–Ar and zircon SHRIMP geochronology from ophiolite and rhyolite in Guoganjianian. *Acta Petrologica Sinica* 23, 911–918 (in Chinese with English abstract).
- Li, G., Kohn, B., Sandiford, M., Xu, Z., 2017. India-Asia convergence: Insights from burial and exhumation of the Xigaze fore-arc basin, south Tibet. *Journal of Geophysical Research: Solid Earth* 122, 3430–3449. doi:10.1002/2017JB014080.
- Li, J.X., Qin, K.Z., Li, G.M., Richards, J.P., Zhao, J.X., Cao, M.J., 2014. Geochronology, geochemistry, and zircon Hf isotopic compositions of Mesozoic intermediate–felsic intrusions in central Tibet: petrogenetic and tectonic implications. *Lithos* 198–199, 77–91.
- Li, S., Ding, L., Guilmette, C., Fu, J.J., Xu, Q., Yue, Y.H., Pinto R.H., 2017a. The subduction–accretion history of the Bangong–Nujiang Ocean: Constraints from provenance and geochronology of the Mesozoic strata near Gaize, central Tibet. *Tectonophysics* 702, 42–60.

- Li, S., Guilmette, C., Ding, L., Xu, Q., Fu, J.J., Yue, Y.H., 2017b. Provenance of Mesozoic clastic rocks within the Bangong–Nujiang suture zone, central Tibet: Implications for the age of the initial Lhasa–Qiangtang collision. *Journal of Asian Earth Sciences* 147, 469–484.
- Liu, D., Huang, Q., Fan, S., Zhang, L., Shi, R., Ding, L., 2014. Subduction of the BangongNujiang Ocean: constraints from granites in the Bangong Co area, Tibet. *Geological Journal* 49, 188–206.
- Liu, D., Shi, R., Ding, L., Huang, Q., Zhang, X., Yue, Y., Zhang, L., 2017. Zircon U–Pb age and Hf isotopic compositions of Mesozoic granitoids in southern Qiangtang, Tibet: implications for the subduction of the Bangong–Nujiang Tethyan Ocean. *Gondwana Research* 41, 157–172.
- Liu, L., Qiu, J.S., Li, Z., 2013. Origin of mafic microgranular enclaves (MMEs) and their host quartz monzonites from the Muchen pluton in Zhejiang Province, Southeast China: implications for magma mixing and crust–mantle interaction. *Lithos* 160–161, 145–163.
- Liu, W.B., Qian, Q., Yue, G.L., Li, Q.S., Zhang, Q., Zhou, M.F., 2002. The geochemical characteristics of fore–arc ophiolite from Dengqen area, Tibet. *Acta Petrologica Sinica* 18, 392–400 (in Chinese with English abstract).
- Lowe, D. R., 1979. Sediment gravity flows: their classification and some problems of application to natural flows and deposits. *SEPM Special Publication* 27, 75–82.
- Ludwig, K.R., 2001. Isoplot/Ex (rev. 2.49): a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center, Special Publication 1, 1–58.
- Ma, A., Hu, X., Garzanti, E., Han, Z., Lai, W., 2017. Sedimentary and tectonic evolution of the southern Qiangtang basin: Implications for the Lhasa–Qiangtang collision timing. *Journal of Geophysical Research: Solid Earth* 122, doi:10.1002/2017JB014211.

- Mo, X.X., Hou, Z.Q., Niu, Y.L., Dong, G.C., Qu, X.M., Zhao, Z.D., Yang, Z.M., 2007. Mantle contributions to crustal thickening during continental collision: evidence from Cenozoic igneous rocks in southern Tibet. *Lithos* 96, 225–242.
- Mo, X.X., Niu, Y.L., Dong, G.C., Zhao, Z.D., Hou, Z.Q., Zhou, S., Ke, S., 2008. Contribution of syncollisional felsic magmatism to continental crust growth: a case study of the Paleogene Linzizong Volcanic Succession in southern Tibet. *Chemical Geology* 250, 49–67.
- Mutti, E., and Ricci Lucchi, F., 1978. Turbidites of the northern Apennines: introduction to facies analysis: *International geology review* 20, 125–166.
- Mutti, E., 1977. Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South–Central Pyrenees, Spain). *Sedimentology* 24, 107–131.
- Naylor, M.A., 1980. The origin of inverse grading in muddy debris flow deposits—a review. *Journal of Sedimentary Research* 50, 1111–1116.
- Orme, D.A., and Laskowaki, A.K., 2016. Basin Analysis of the Albian–Santonian Xigaze Forearc, Lazi Region, South–Central Tibet. *Journal of Sedimentary Research* 86, 894–913.
- Orme, D.A., Carrapa, B., Kapp, P., 2014. Sedimentology, provenance and geochronology of the upper Cretaceous–lower Eocenewestern Xigaze forearc basin, southern Tibet. *Basin Research*, 1–25.
- Pan, G., Wang, L., Li, R., Yuan, S., Ji, W., Yin, F., Zhang, W., Wang, B., 2012. Tectonic evolution of the Qinghai–Tibet plateau. *Journal of Asian Earth Sciences* 53, 3–14.
- Pan, G., Zheng, H., Xu, Y., 1983. A Preliminary Study on Bangong Co–Nujiang Suture. *Geological Memoirs of Qinghai–Xizang Plateau* (12)—Geological Tectonics of

- “Sanjiang”. Geological Publishing House, Beijing, pp. 229–242 (in Chinese with English abstract).
- Pan, G.T, Ding, J., Yao, D.S., Wang, L.Q., 2004. Guide book of 1: 1, 500, 000 geologic map of the Qinghai–Xizang (Tibet) plateau and adjacent areas. Cartographic Publishing House, Chengdu, China, 1–148pp.
- Peng, T., Zhao, G., Fan, W., Peng, B., Mao, Y., 2015. Late Triassic granitic magmatism in the Eastern Qiangtang, Eastern Tibetan Plateau: geochronology, petrogenesis and implications for the tectonic evolution of the Paleo–Tethys. *Gondwana Research* 27, 1494–1508.
- Pullen, A., Kapp, P., Gehrels, G.E., Ding, L., Zhang, Q., 2011. Metamorphic rocks in central Tibet: lateral variations and implications for crustal structure. *Geological Society of America Bulletin* 123, 585–600.
- Pullen, A., Kapp, P., Gehrels, G.E., Vervoort, J.D., Ding, L., 2008. Triassic continental subduction in central Tibet and Mediterranean–style closure of the Paleo–Tethys Ocean. *Geology* 36, 351–354
- Qiu, R.Z., Zhou, S., Deng, J.F., Li, J.F., Xiao, Q.H., 2004. Dating of gabbro in the Shemalagou ophiolite in the western segment of the Bangong–Nujiang ophiolite belt, Tibet—with a discussion of the age of the Bangong Co–Nujiang ophiolite belt. *Geology in China* 31, 262–268 (in Chinese with English abstract).
- Schweller, W.J., Kulm, L.D., Prince, R.A., 1981. Tectonics, structure, and sedimentary framework of the Peru–Chile Trench. In: Kulm, L.D., Dymond, J., Dasch, E.J., Hussong, D.M. (Eds.), *Nazca Plate: Crustal formation and Andean convergence*. Geological Society of America Memoir 154, 323–349.

- Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Rex, D.C., Li, T.D., Xiao, X.C., Jan, Q., Thakur, V., and Kumar, S., 1987. The closing of Tethys and the tectonics of the Himalaya. *Geological Society of America Bulletin* 98, 678–701.
- Shi, R., 2007. SHRIMP dating of the Bangong Lake SSZ-type ophiolite: constraints on the closure time of ocean in the Bangong Lake–Nujiang River, northwestern Tibet. *Chinese Science Bulletin* 52, 936–941.
- Shi, R., Alard, O., Zhi, X., O'Reilly, S.Y., Pearson, N.J., Griffin, W.L., Zhang, M., Chen, X., 2007. Multiple events in the Neo–Tethyan oceanic upper mantle: evidence from Ru–Os–Ir alloys in the Luobusa and Dongqiao ophiolitic podiform chromitites, Tibet. *Earth and Planetary Science Letters* 261, 33–48.
- Shi, R., Griffin, W.L., O'Reilly, S.Y., Huang, Q., Zhang, X., Liu, D., Zhi, X., Xia, Q., Ding, L., 2012. Melt/mantle mixing produces podiform chromite deposits in ophiolites: implications of Re–Os systematics in the Dongqiao Neo–tethyan ophiolite, northern Tibet. *Gondwana Research* 21, 194–206.
- Shi, R., Yang, J., Xu, Z., Qi, X., 2008. The Bangong Lake ophiolite (NW Tibet) and its bearing on the tectonic evolution of the Bangong–Nujiang suture zone. *Journal of Asian Earth Sciences* 32, 438–457.
- Shi, R.D., Yang, J.S., Xu, Z.Q., Qi, X.X., 2004. Discovery of the boninite series volcanic rocks in the Bangong Lake ophiolite mélangé, western Tibet, and its tectonic implications. *Chinese Science Bulletin* 49, 1272–1278.
- Soderlund, U., Patchett, P.J., Vervoort, J.D., and Isachsen, C.E., 2004. The ^{176}Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters* 219, 311–324.

- Sun, G.Y., Hu, X.M., Sinclair, H.D., 2017. Early Cretaceous palaeogeographic evolution of the Coqen Basin in the Lhasa Terrane, southern Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology* 485, 101–118.
- Sun, G.Y., Hu, X.M., Zhu, D.C., Hong, W.T., Wang, J.G., Wang, Q., 2015a. Thickened juvenile lower crust–derived ~90 Ma adakitic rocks in the central Lhasa terrane, Tibet. *Lithos* 224–225, 225–239.
- Sun, G.Y., Hu, X.M., Sinclair, H.D., Marcelle, B.K., Wang, J.G., 2015b. Late Cretaceous evolution of the Coqen basin (Lhasa terrane) and implications for early topographic growth on the Tibetan Plateau. *Geological Society of America Bulletin* 127, 1001–1020.
- Tang, X., and Zhang, K., 2014. Lawsonite–and Glaucophane-bearing Blueschists from NW Qiangtang, Northern Tibet, China: mineralogy, geochemistry, geochronology, and tectonic implications. *International Geology Review* 56, 150–166.
- Thornburg, T. M., Kulm, D.M., Hussong, D.M., 1990. Submarine-fan development in the southern Chile trench: A dynamic interplay of tectonics and sedimentation, *Geological Society of America Bulletin* 102, 1658–1680.
- Underwood, M. B., and Moore, G. F., 1995. Trenches and trench–slope basins, in Busby, C. J., and Ingersoll, R. V., eds., *Tectonics of sedimentary basins*: Cambridge, Blackwell Science, p. 179–220.
- Van Achterbergh, E., Ryan, C.G., Jackson, S.E., Griffin, W.L., 2001. Data reduction software for LA–ICPMS: appendix. *Laser ablation–ICP–mass spectrometry in the earth sciences: principles and applications: Short Course Series*, 29. Ottawa, Ontario, Mineralogical Association of Canada, 239–243.

- Wang J G, Hu X M, Jansa L, Huang Z C. 2011. Provenance of the Upper Cretaceous–Eocene Deep–Water sandstones in Sangdanlin, Southern Tibet: Constraints on the timing of initial India–Asia collision. *Journal of Geology* 119, 293–30
- Wang, B.D., Wang, L.Q., Chung, S. L., Che, J.L., Yin, F.G., Liu, H., Li, X.B., Chen, L.K., 2016. Evolution of the Bangong–Nujiang Tethyan ocean: Insights from the geochronology and geochemistry of mafic rocks within ophiolites. *Lithos* 245, 18–33.
- Wang, C., and Liu, Z., 1999. Xigaze forearc basin and Yarlung Zangbo suture zone, Tibet (in Chinese): Beijing, Geological Publishing House, 237 pp.
- Wang, C., Li, X., Liu, Z., Li, Y., Jansa, L., Dai, J., Wei Y., 2012. Revision of the Cretaceous–Paleogene stratigraphic framework, facies architecture and provenance of the Xigaze forearc basin along the Yarlung Zangbo suture zone. *Gondwana Research* 22, 415–433.
- Wang, J., Wang, Z., Chen, W., Fu, X., 2007. New evidences for the age assignment of the Nadi Kangri Formation in the North Qiangtang depression, northern Tibet, China. *Geological Bulletin of China* 26, 404–409 (in Chinese with English abstract).
- Wang, J.G., Hu, X.M., BouDagher-Fadel, M., Wu, F.Y., Sun, G.Y., 2015. Early Eocene sedimentary recycling in the Kailas area, southwestern Tibet: Implications for the initial India–Asia collision. *Sedimentary Geology* 315, 1–13.
- Wang, W.L., Aitchison, J.C., Lo, C.H., Zeng, Q.G., 2008. Geochemistry and geochronology of the amphibolite blocks in ophiolitic mélanges along Bangong–Nujiang suture, central Tibet. *Journal of Asian Earth Sciences* 33, 122–138.
- Wang, X.L., Zhou, J.C., Wan, Y.S., Kitajima, K., Wang, D., Bonamici, C., Qiu, J.S., Sun, T., 2013. Magmatic evolution and crustal recycling for Neoproterozoic strongly peraluminous granitoids from southern China: Hf and O isotopes in zircon. *Earth and Planetary Science Letters* 366, 71–82.

- Wen, D.R., Liu, D.Y., Chung, S.L., Chu, M.F., Ji, J.Q., Zhang, Q., Song, B., Lee, T.Y., Yeh, M.W., Lo, C.H., 2008. Zircon SHRIMP U–Pb ages of the Gangdese Batholith and implications for Neotethyan subduction in southern Tibet. *Chemical Geology* 252, 191–201.
- Winn, R.D., and Dott, R.H., 1979. Deep–water fan–channel conglomerates of Late Cretaceous age, southern Chile. *Sedimentology* 26, 203–228.
- Wu, F.Y., Ji, W.Q., Liu, C.Z., Chung, S.L., 2010. Detrital zircon U–Pb and Hf isotopic data from the Xigaze forearc basin: Constraints on Transhimalayan magmatic evolution in southern Tibet. *Chemical Geology* 271, 13–25.
- XZBGM (Xizang Bureau of Geology and Mineral Resources), 1993. Regional geology of Xizang Autonomous Region, China, with geologic map. Beijing, Geological Publishing House 707 p., scale 1:1,500,000.
- Yan, M., Zhang, D., Fang, X., Ren, H., Zhang, W., Zan, J., Song, C., Zhang, T., 2016. Paleomagnetic data bearing on the Mesozoic deformation of the Qiangtang Block: implications for the evolution of the Paleo–and Meso–Tethys. *Gondwana Research* 39, 292–316.
- Yang, T.N., Zhang, H.R., Liu, Y.X., Wang, Z.L., Song, Y.C., Yang, Z.S., Tian, S.H., Xie, H.Q., Hou, K.J., 2011. Permo–Triassic arc magmatism in central Tibet: evidence from zircon U–Pb geochronology, Hf isotopes, rare earth elements, and bulk geochemistry. *Chemical Geology* 284, 270–282.
- Yin, A., and Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen: *Annual Review of Earth and Planetary Sciences* 28, 211–280.
- Yin, J., Xu, J., Liu, C., Li, H., 1988. The Tibetan Plateau: Regional stratigraphic context and previous work. *Philosophical Transactions of the Royal Society of London, series A* 327, 5–52.

- Zeng, M., Zhang, X., Cao, H., Effensohn, F.R., Cheng, W., Lang, X., 2015. Late Triassic initial subduction of the Bangong–Nujiang Ocean beneath Qiangtang revealed: stratigraphic and geochronological evidence from Gaize, Tibet. *Basin Research* 28, 147–157.
- Zeng, Q.G., Mai, G.Z., Chen, G.R., 2006. 1: 250,000 geological map of Gaize region with report. Bureau of Geology and Mineral Resources of Xizang Autonomous Region, Lhasa (in Chinese with English abstract).
- Zhai, Q.G., Jahn, B.M., Su, L., Wang, J., Mo, X.X., Lee, H.Y., Wang, K.L., Tang, S., 2013. Triassic arc magmatism in the Qiangtang area, northern Tibet: zircon U–Pb ages, geochemical and Sr–Nd–Hf isotopic characteristics, and tectonic implications. *Journal of Asian Earth Sciences* 63, 162–178.
- Zhai, Q.G., and Li, C., 2007. Zircon SHRIMP dating of volcanic rock from Nadigangri Formation in Juhuashan, Qiangtang, Northern Tibet and its geological significance. *Acta Geologica Sinica* 81, 795–800 (in Chinese with English abstract).
- Zhai, Q.G., Zhang, R.Y., Jahn, B.M., Li, C., Song, S.G., Wang, J., 2011. Triassic eclogites from central Qiangtang, northern Tibet, China: petrology, geochronology and metamorphic P–T path. *Lithos* 125, 173–189.
- Zhang, K.J., Xia, B.D., Wang, G.M., Li, Y.T., Ye, H.F., 2004. Early Cretaceous stratigraphy, depositional environments, sandstone provenance, and tectonic setting of central Tibet, western China. *Geological Society of America Bulletin* 116, 1202–1222.
- Zhang, K.J., Zhang, Y.X., Li, B., Zhong, L.F., 2007. Nd isotopes of siliciclastic rocks from Tibet, western China: constraints on provenance and pre–Cenozoic tectonic evolution. *Earth and Planetary Science Letters* 256, 604–616.

- Zhang, K.J., Zhang, Y.X., Tang, X.C., Xia, B., 2012. Late Mesozoic tectonic evolution and growth of the Tibetan plateau prior to the Indo–Asian collision. *Earth-Science Reviews* 114, 236–249.
- Zhang, Q., Ding, L., Cai, F., Xu, X., Zhang, L., Xu, Q., and Willems, H., 2011. Early Cretaceous Gangdese retroarc foreland basin evolution in the Selin Co basin, central Tibet: evidence from sedimentology and detrital zircon geochronology. *Geological Society, London, Special Publications* 353, 27–44.
- Zhu, D.C., Li, S.M., Cawood, P.A., Wang, Q., Zhao, Z.D., Liu, S.A., Wang, L.Q., 2016. Assembly of the Lhasa and Qiangtang terranes in central Tibet by divergent double subduction. *Lithos* 245, 7–17.
- Zhu, D.C., Mo, X.X., Niu, Y.L., Zhao, Z.D., Wang, L.Q., Liu, Y.S., Wu, F.Y., 2009. Geochemical investigation of Early Cretaceous igneous rocks along an east–west traverse throughout the central Lhasa Terrane, Tibet. *Chemical Geology* 268, 298–312.
- Zhu, D.C., Mo, X.X., Zhao, Z.D., Xu, J.F., Zhou, C.Y., Sun, C.G. Wang, L.Q., Chen, H.H., Dong, G.C., Zhou, S., 2008. Zircon U–Pb geochronology of Zenong Group volcanic rocks in Coqen area of Gangdese, Tibet and tectonic significance. *Acta Petrologica Sinica* 24, 401–412 (in Chinese with English abstract).
- Zhu, D.C., Wang, Q., Zhao, Z.D., Chung, S.L., Cawood, P.A., Niu, Y.L., Liu, S.A., Wu, F.Y., Mo, X.X., 2015. Magmatic record of India–Asia collision. *Scientific Reports* 5, 14289, <http://dx.doi.org/10.1038/srep14289>.
- Zhu, D.C., Zhao, Z.D., Niu, Y., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and pre–Cenozoic evolution of the Tibetan Plateau. *Gondwana Research* 23, 1429–1454.
- Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q., and Wu, F.Y., 2011a. The Lhasa Terrane: Record of a microcontinent and its histories of drift and growth. *Earth and Planetary Science Letters* 301, 241–255.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Mo, X.X., 2011b. Lhasa terrane in southern Tibet came from Australia. *Geology* 39, 727–730.

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Figure captions

Fig. 1 a) Tectonic framework of the Tibetan plateau, JSSZ—Jinsha suture zone; BNSZ = Bangong–Nujiang suture zone; IYSZ = Yarlung–Zangbo suture zone; b) Simplified geological map of the Dong Co area, central Tibet (Zeng et al., 2006). The dashed line represents the boundary between Muganggri Group *mélange* ($J_{1-2} \text{ mlg}$) and the deep-water turbidites (normal graded strata, $J_{1-2} \text{ m}$).

Fig. 2 Lithological columns of the Gamulong Formation in the study area; the Latitude and longitude data correspond to the start and end point of the section.

Fig. 3 a) Panoramic photograph for the Gamulong Formation, showing the relationships with the other strata; b) The conglomerate bodies in the section; c) Clast-supported cobble conglomerate beds. Hammer is 41 cm long; d) Matrix-supported cobble conglomerate beds. Hammer is 41 cm long; e) The conglomerate beds with imbricated clasts; f) The interbedded lenticular or wedge-shaped pebbly coarse-grained sandstones. Hammer is 41 cm long; g) Coarse-grained sandstone beds. Hammer is 41 cm long; h) the mudstone beds with the erosional bases on the top.

Fig. 4 Petrography of the Gamulong Formation. a) Sandstone pebble with abundant sedimentary clasts; b) Microcrystalline limestone pebble showing recrystallization locally; c) and d) Interbedded sandstones with abundant sedimentary clasts; e) *Andersenolina elongata* ;f) *Neotrocholina sp.*

Fig. 5 The Ternary diagrams of sandstone framework compositions from the Gamulong Formation (Referred to Dickinson, 1985; Garzanti et al., 2007). Q = quartz; F = feldspar; Lm = metamorphic fragments; Lv = volcanic fragments; Ls = sedimentary fragments; L = lithic fragments (Lm + Lv + Ls). The data of Muganggri Group and Sewa Formation are from Li et al. (2017a) and Ma et al. (2017).

Fig. 6 Relative U-Pb age probabilities for detrital zircons from the sandstones of the Gamulong Formation. 16GM12 is the sandstone pebble, 16GM19 and 17LY01 are the sandstone matrix.

Fig. 7 Plots of $\varepsilon_{Hf}(t)$ values versus the U-Pb ages of zircons from sandstones within the Gamulong Formation (this study), Muganggri Group (Li et al., 2017a), and Sewa Formation (Huang et al., 2017; Ma et al., 2017).

Fig. 8 Comparisons of probability density diagrams of zircon ages from the Gamulong Formation (this study) to reference age populations from the Lhasa terrane (Leier et al., 2007b; Gehrels et al., 2011; Zhu et al., 2011b), Qiangtang terrane (Leier et al., 2007b; Pullen et al., 2008, 2011; Dong et al., 2011; Gehrels et al., 2011; Zhu et al., 2011b), igneous rocks of Qiangtang terrane (Guynn et al., 2006; Li et al., 2007; Wang et al., 2007; Zhai and Li, 2007; Pullen et al., 2008; Zhai et al., 2013; Li et al., 2014; Liu et al., 2014, 2017; Peng et al., 2015), Muganggri Group (Zeng et al., 2015; Huang et al., 2017; Li et al., 2017a) and Sewa Formation (Huang et al., 2017; Ma et al., 2017).

Fig. 9 Two possible tectonic models of the Gamulong Formation (not to scale), showing the trench deposits in response to (a) the northward subduction of the Bangong-Nujiang oceanic lithosphere, or (b) the initial Lhasa-Qiangtang collision.

Research Highlights

- ▶ Discovery of the Middle Jurassic trench deposits in the Bangong-Nujiang suture zone
- ▶ Featuring the sedimentary recycling from the Bangong-Nujiang suture zone and southern Qiangtang subterrane
- ▶ Implications for Lhasa-Qiangtang initial collision at Middle Jurassic

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

(a) Model 1: subduction

(b) Model 2: initial collision

Figure 9