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Sedimentology and provenance of newly identified Upper Cretaceous trench basin strata, Dênggar, southern Tibet: Implications for development of the Eurasian margin prior to India-Asia collision

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ABSTRACT

Trench basins preserved along the southern margin of the Lhasa Terrane, Tibet are sedimentologic records of convergent margin processes preceding Cenozoic India-Asia collision. We present new sedimentologic, petrographic and geochronologic data from the Rongmawa Formation and surrounding strata near Dênggar, Tibet to determine depositional environment, provenance, and age. Depositional ages range from ~92-87 Ma and lithofacies are consistent with deposition by low- and high-density turbidity currents and suspension settling of pelagic detritus in a deep-marine, trench basin setting. Sandstone modal analyses and U-Pb geochronology indicate trench basin detritus in this region was derived from the Lhasa Terrane. We interpret that the Cretaceous subduction trench received detritus from an axial sediment dispersal system that transported sediment from headwaters in the central-southern Lhasa terrane near Lhasa City directly to the trench and then flowed westward parallel to the trench, depositing detritus in trench basins. Preservation of trench basin strata deposited during Late Cretaceous time compared with the lack of trench deposits prior to ~ 92 Ma and after ~ 80 Ma suggests

the margin experienced a period of significant accretion during this interval. In addition, deposition of trench basin strata occurred during Late Cretaceous adakitic magmatism and high-temperature metamorphism, which are hypothesized to be explained by subduction of an oceanic ridge or subduction zone retreat and related upper-plate extension along the southern margin of the Lhasa terrane. Subduction of an oceanic ridge may provide a mechanism to potentially erode forearc basin strata and promote increased sediment delivery directly to the trench.

INTRODUCTION

Trench basins, which form oceanward of magmatic arc-forearc basin systems on the slope between the trench and subduction complex, are sedimentary records of the tectonic evolution of convergent margins (Moore and Karig, 1976). Whether ocean trenches are sediment starved (<1 km sediment thickness) or sediment rich (> 5 km) depends on a number of factors, including proximity to major sediment routing systems and whether plate dynamics (i.e., convergence rate vs. subduction rate) promote sediment accretion or sediment erosion at the trench (e.g., Karig, 1974; Royden, 1993; Stern, 2002; Vannucchi et al. 2013). In ancient systems, trench basins are often interpreted to represent periods of accretion along a convergent margin and the absence or scarcity of trench sedimentary fill has been used to argue for periods of subduction erosion (e.g., Scholl et al., 1970; Karig and Sharman, 1975; Becerra et al., 2013).

The Yarlung suture zone (YSZ) in southern Tibet preserves lithotectonic units developed during Middle Triassic-earliest Cenozoic northward subduction of Neo-Tethyan oceanic lithosphere along the southern margin of Asia, namely the Gangdese magmatic arc, Xigaze forearc basin, and a subduction complex. Although subduction related magmatism is documented since the Middle Triassic, forearc basin and subduction complex stratigraphic records are incomplete. This has led to reconstructions of alternating periods of accretion and erosion in southern Tibet prior to India-Asia collision during early Cenozoic time (An et al., 2018; Metcalf and Kapp, 2019). Recent discovery of Cretaceous trench basin strata deposited atop the subduction complex or in a trench-slope setting has contributed to these models (Cai et al., 2012; An et al., 2018; Wang et al., 2018; Fu et al., 2018; Laskowski et al. 2019), which placed in the context of other geologic data, can be used to interpret large-scale plate dynamic changes. Discovery of trench basin strata deposited during Late Cretaceous time is particularly significant because it corresponds in time to an episode of high-temperature metamorphism and adakitic magmatism in the southern Lhasa terrane (e.g. Kapp and DeCelles, 2019). We highlight the relevance of the trench basin record for testing hypotheses about the tectonic processes that were active during this time, which include: oceanic ridge subduction and subduction zone retreat driving upper-plate extension (Kapp and DeCelles, 2019). The latter possibility is hypothesized to have created a back-arc basin along the southern Asian margin (Kapp and DeCelles, 2019).

This study examines newly discovered strata of the Rongmawa Formation in southern Tibet to reconstruct the paleodepositional environment and paleogeography of the southern margin of Asia during Late Cretaceous time and test different tectonic models for the evolution of the Eurasian convergent margin over a period of more than 30 Myr leading up to the onset of collisional orogeny along the YSZ. We report sedimentologic, modal petrographic and U-Pb geochronologic data from clastic sedimentary rocks preserved north of the town of Dênggar in Saga County. We show that these rocks were deposited in a deep-marine, trench basin setting and that detritus was derived from magmatic arc rocks near Lhasa city, consistent with previous provenance interpretations (Laskowski et al. 2019). These results constrain tectonic and paleogeographic models by requiring the existence of plausible sediment dispersal networks between sources and the basin throughout the period of trench basin deposition.

GEOLOGIC SETTING

Lithotectonic Units

The YSZ extends for ~ 1200 km across southern Tibet and represents the boundary between rocks of Asian affinity in the north from those deposited on the Indian passive margin to the south. From north to south, the suture zone consists of assemblages formed during northward subduction of Neo-Tethyan oceanic lithosphere, namely the Mesozoic-Paleogene Gangdese magmatic arc, Cretaceous-Eocene Xigaze forearc basin, Jurassic and Cretaceous ophiolites, and Jurassic-Paleocene subduction complex (Figure 1).

The Gangdese magmatic arc intrudes the Lhasa terrane, a Gondwanan terrane that accreted to the southern margin of Asia in Middle Jurassic (Ma et al. 2017; Sun et al., 2019) or earliest Cretaceous time (Dewey et al., 1988; Kapp et al., 2007; Chen et al., 2020). The magmatic arc primarily consists of calc-alkaline batholith that was active as early as Middle to Late Triassic until Paleogene time (Chu et al., 2006; Ji et al., 2009; Zhu et al., 2011; Guo et al., 2013; Ma et al., 2017; Wang et al. 2017) and a volcanic edifice represented by the ~69-38 Ma Linzizong Formation (He et al., 2007; Zhu et al., 2018). Igneous U-Pb ages derived from the Gangdese arc are consistently < 250 Ma, with high flux events evident by spatially variable age peaks at ~70-45 Ma, ~100-78 Ma, ~120-140 Ma, ~195-175 Ma and ~200-220 Ma; there are distinct periods of minimal magmatic activity (i.e., magmatic lulls) from 174-156 Ma, 132-120 Ma (in the southern Lhasa terrane) and ~78-70 Ma (Zhu et al. 2008; 2011; Ji et al., 2009, Kang et al., 2014; Wei et al., 2017; Wang et al., 2018). By contrast, the Lhasa terrane comprises pre-Mesozoic U-Pb age peaks of 500-560 Ma, 800-950 Ma, 1000-1300 Ma, 1500-2000 Ma and 2500-3200 Ma (Gehrels et al. 2011). The Zedong arc, which locally outcrops near the town of Zedong southeast of Lhasa (Figure 1), contains a distinct 160-155 Ma age peak. Based on the stratigraphy and geochemistry at this locality, the Zedong arc is interpreted to have formed either above an intra-oceanic subduction zone and was accreted to the northern margin of India or the southern Lhasa terrane (e.g., Cao, 1981; Aitchison et al., 2000, 2003, 2007, 2011; Malpas et al., 2003; Ziabrev et al., 2003, 2004; Hebert et al., 2012; Baxter et al., 2016) or as the juvenile Jurassic part of the Gangdese magmatic arc (Zhang et al., 2014; Hu et al., 2016; Metcalf and Kapp, 2019).

South of the Gangdese magmatic arc is the Xigaze forearc basin (Figure 1). The Xigaze forearc extends for ~ 500 km along the YSZ and is separated from the Oligocene-Miocene Kailas Formation to the north and subduction complex to the south by splays of the north-vergent Great Counter Thrust system (GCT). The Xigaze forearc basin preserved along the YSZ was primarily deposited during Cretaceous-Eocene time and consists of an overall fining-upward succession of deep-marine turbidites to shallow-marine and fluvial sedimentation (Einsele et al., 1994; Dürr, 1996; Wu et al., 2010; An et al., 2014; Orme et al., 2015; Orme and Laskowski, 2016; Wang et al. 2017). Sandstones from the forearc have a magmatic arc provenance and show a volcanic to plutonic unroofing trend through time (An et al., 2014; Orme et al., 2015). U-Pb detrital zircon age spectra reflect age peaks derived from the Lhasa terrane and southern Gangdese magmatic arc, with peaks at ~158 Ma, ~110 Ma, ~ 90 Ma, and ~60 Ma (Wu et al., 2010; Wang et al., 2012; An et al., 2014; Orme et al., 2015; Wang et al., 2017), but also the episodic appearance of 120-140 Ma zircons derived from the northern Lhasa terrane (Leier et al., 2007; Orme and Laskowski, 2016). Recent discovery of turbiditic and carbonate deposits with an undissected arc provenance and detrital zircon age peak of ~ 158 Ma along the YSZ, termed the Xiazha Formation, suggests an earlier period of Jurassic forearc basin development (Metcalf and Kapp, 2019). This discovery supports a model whereby the margin may have experienced a period of significant erosion prior to deposition of Cretaceous-Eocene forearc strata.

South of the Xigaze forearc basin, in fault contact along a north-vergent strand of the GCT, are a series of Jurassic-Cretaceous ophiolites and ophiolitic mélange consisting of fragments of serpentinized mantle peridotite, gabbro, sheeted dikes, pillow basalt and radiolarian chert (e.g., Göpel et al., 1984; Malpas et al., 2003; Guilmette et al., 2007; Dai et al., 2012; Wang et al., 2017; Figure 1). The ophiolites are Jurassic-Cretaceous in age (Zhou et al., 1982; Gopel et al., 1984; Malpas et al., 2003; Ziabrev et al. 2003) and are interpreted to have been formed in a surprasubduction-forearc setting (Dai et al., 2013; An et al., 2014; Wu et al., 2014; Maffione et al., 2015; Huang et al., 2015; Xiong et al., 2016; 2017) or in the forearc or back-arc of an intraoceanic arc (Aitchison et al., 2000, 2003; Malpas et al. 2003; Ziabrev et al., 2003; Abrajevitch et al., 2005; Guilmette et al., 2009, 2012; Herbet et al. 2012; Chan et al., 2015; Baxter et al., 2016). Cretaceous strata of the Xigaze forearc basin are found in depositional contact atop fragments of the ophiolite, suggesting at least some of the ophiolite formed in the forearc of the southern Lhasa terrane (Liu et al., 2015; Huang et al., 2015; Orme and Laskowski, 2016, Laskowski et al., 2017).

The YSZ subduction complex, located south of the ophiolite and north of the Tethyan Himalaya, primarily consists of a siliciclastic-matrix mélange and trench basin units (Figure 1). The siliciclastic-matrix mélange is composed of basalt, metabasite, chert, limestone, sandstone and shale blocks intercalated with purple and green shale, sandstone and chert (Shackleton, 1981; Tapponnier et al., 1981; Dupuis et al., 2005; Cai et al., 2012; Li et al., 2015; An et al., 2017; Metcalf and Kapp, 2017; Wang et al., 2017; Metcalf and Kapp, 2019). Near the town of Sangsang, there are local outcrops of blueschist within the mélange (Ding et al., 2005; Wang et al., 2018). U-Pb detrital zircon age peaks within the siliciclastic-matrix mélange range from Permian to Paleocene and reflect both Lhasa terrane and Tethyan Himalaya affinity (Cai et al., 2012, An et al., 2017; Metcalf and Kapp, 2017, 2019). Maximum depositional ages (MDA) of blocks within the mélange often reflect depositional ages observed in the Xigaze forearc basin to the north (e.g., Metcalf and Kapp, 2017), indicating they are genetically related.

However, in contrast to the forearc, there are no MDAs within the siliciclastic-matrix mélange younger than ~ 78 Ma (Metcalf and Kapp, 2019).

Trench-strata of the subduction complex are documented along the YSZ, southeast of Xigaze to the Saga region (Figure 1). Trench-strata consists of the Rongmawa, Luogangcuo, and Jiachala formations, which were deposited during the latest Cretaceous (Cai et al., 2012; Wang et al., 2018; An et al., 2018; Fu et al., 2018; Laskowski et al., 2019). The Rongmawa Formation was first discovered near the town of Ngamring and is divided into a lower and middle member, consisting of chert, basalt, and red and green mudrock, and turbiditic upper member (Figure 1; Cai et al., 2012). Similarly, Wang et al. (2018) document turbiditic sandstones near Sangsang (Figure 1) and interpret them as part of the Rongmawa Formation based on lithologies and Cretaceous MDAs. Metcalf and Kapp (2019) only consider the turbiditic upper member to be deposited in a trench-slope setting and the lower and middle members to be deposited as part of the siliciclastic-matrix mélange. Sandstones from the Rongmawa Formation are sub-litharenites and plot within the recycled orogen field of Dickinson et al., (1983) (Cai et al., 2012; Metcalf and Kapp, 2019). The most recent discovery of Rongmawa Formation, and focus of this paper, is preserved near Dênggar, ~60 km east-southeast of Saga (Laskowski et al. 2019; Figure 1 and 2). The Luogangcuo Formation is a conglomeratic and turbiditic unit that overlies siliciclastic-matrix mélange in fault contact due south of Saga (Figure 1; An et al. 2018). Sandstones from the Luogangcuo Formation are predominantly feldspathic litharenites and litharenites and plot within transitional arc to dissected arc fields of Dickinson et al. (1983) (An et al. 2018). The Jiachala Formation, preserved southeast of Xigaze, consists of deep-marine turbidites deposited during latest Cretaceous (~88-84 Ma) (Figure 1; Wei et al., 2006; Cai et al., 2013; Wu et al., 2014; Fu et al., 2018). Sandstones from the Jiachala Formation are sub-litharenites and, integrated with detrital zircon age spectrum and Hf isotope ratios, indicate provenance from the Gangdese arc and central Lhasa terrane

(Cai et al., 2008; Wu et al., 2014; Fu et al., 2018). Trench-strata of the YSZ have a range of MDAs of ~140-59 Ma (Metcalf and Kapp, 2019), but most strata of the Rongmawa, Luogangcuo, and Jiachala formations have MDAs of 92-80 Ma and a detrital zircon age spectrum consistent with derivation from Asia (Cai et al., 2008; Cai et al., 2012; Wang et al., 2018; An et al., 2018; Fu et al., 2018; Laskowski et al., 2019). Notably, the Rongmawa and Jiachala formations contain a distinct ~200-220 Ma age peak that is absent from the Luogangcuo Formation, suggesting the latter was derived from different sediment dispersal systems along the Asian southern margin (Laskowski et al., 2019).

South of the subduction complex is the Tethyan Himalaya, which is composed of low-grade to unmetamorphosed Paleozoic and Mesozoic (meta-)sedimentary rocks originally deposited on the passive margin of the Indian continent (Burg et al., 1987; Ratschbacher et al., 1994). A series of mylonitic orthogneiss and paragneiss domes disrupt the generally north verging thrust sheets of Tethyan Himalayan strata (e.g., Murphy et al., 2003; Jessup et al., 2019). Detrital zircons from the Tethyan Himalaya are > 400 Ma, with the exception of local volcaniclastic peaks such as the 145-115 Ma peak from the Wölong Formation (Hu et al., 2015) and Paleocene age peaks related to India-Asia collision (e.g., Ding et al., 2005; DeCelles et al. 2014; Cai et al., 2011, Wang et al., 2017). The predominant age peaks within the Tethyan Himalaya are ca. 500-560 Ma, 1000-1300 Ma, and 2500-3200 Ma (Gehrels et al. 2011).

Late Cretaceous Tectono-Thermal Events and Explanations

The geology of the Lhasa terrane records major tectono-thermal activity during Late Cretaceous time (~90-70 Ma; Kapp and DeCelles, 2019). Ninety-four to 80 Ma adakites and 90 to 81 Ma granulite-facies metamorphic rocks have been documented in the eastern portion of the Gangdese magmatic arc (Figure 1; Zhang et al., 2010; Jiang et al., 2012; Guo et al., 2013; Zhang et al., 2014). In the northern

Gangdese arc, within the northern Lhasa terrane, 94 to 80 Ma adakitic rocks and tholeiitic basalts have also been documented (Meng et al., 2014; Wang et al., 2014; Chen et al., 2015; Ma et al., 2015; Sun et al., 2015). Within the YSZ, the Xigaze forearc basin appears to have experienced decreased accumulation between 88 and 78 Ma (Wang et al., 2012; Orme and Laskowski, 2016). Amphibolite blocks within the YSZ ophiolitic mélange experienced exhumation between 90 and 80 Ma (Malpas et al., 2003; Bao et al., 2013). Following crystallization of the adakitic rocks, the entire Gangdese magmatic arc entered a low-flux phase (magmatic lull) between 78 and 72 Ma (Kapp and DeCelles, 2019). Depending on the reconstruction, India-Asia convergence either increased from ~50 mm/yr to ~140 mm/yr (van Hinsbergen et al., 2011) or decreased from ~75 mm/yr to ~50 mm/yr (Gibbons et al., 2015) between 90 and 80 Ma. Despite these enigmatic events, there is currently little evidence for development of sedimentary basins or deformation events within the Lhasa Terrane between 90-70 Ma, with the exception of the Xigaze forearc basin, which began accumulating sediment ~ 120-110 Ma.

In their recent synthesis of Tibetan geology, Kapp and DeCelles (2019) outline the traditional tectonic interpretation of the Late Cretaceous Eurasian margin and propose an alternative explanation that may better explain the geology. The traditional interpretation is that Cordilleran-style orogeny, ongoing since ~220 Ma, continued throughout this period. In this explanation, the 94 to 80 Ma tectono-thermal events are possibly related to subduction of the Neo-Tethyan oceanic ridge (Zhang et al., 2010; Guo et al., 2013). This explanation provides a mechanism for exhumation and decreased accumulation in the forearc region. Accompanying flat slab subduction explains the magmatic lull in the Lhasa terrane, as magmatism would have been displaced northwards (Ding et al., 2003; Chung et al., 2005; Wen et al., 2008; Guo et al., 2013). The alternative explanation is that the Eurasian margin experienced trench retreat and upper-plate extension to open a back-arc basin in the southern Lhasa terrane. In this explanation, the tectono-thermal event is attributed to asthenospheric upwelling induced by Neo-

Tethyan slab rollback. This alternative explanation, referred to as the Xigaze back-arc basin model, predicts that the southern part of the Gangdese magmatic arc and the entire YSZ rifted southward from the rest of Eurasia beginning at ~90 Ma. Rejuvenation of Gangdese arc magmatism at ~70 Ma is interpreted to represent the beginning of closure of the back-arc basin.

The Upper Cretaceous Rongmawa Formation trench basin strata investigated in this study were deposited during the enigmatic tectono-thermal event that is central to both explanations. The provenance of the Rongmawa Formation strata is therefore an important test of the predicted paleogeography of the Eurasian margin in both models. Furthermore, the dynamics of trench basin formation and accretion can be evaluated in the context of the existing geological record and the proposed tectonic explanations.

METHODS

Field Mapping, sedimentology and stratigraphy

Geologic mapping was conducted at 1:50,000 scale. Stations were located using handheld, consumer-grade GPS. Field maps were georeferenced in ESRI ArcGIS and utilized to create the digital geologic map (Figure 2) based on GPS-located field stations. Dashed contacts were either inferred in the field or traced based on color changes visible in Landsat imagery for areas that were not accessed during field work.

To determine the depositional environment and lithotectonic units of sedimentary rocks in the Dênggar region, one stratigraphic section was measured at the centimeter scale using a Jacob Staff (Figures 3 and 4) and additional sedimentologic descriptions were done at nine field sites throughout the field area (Figure 2). Extensive erosion across river valleys within the Dênggar valley prohibited additional measured sections. We use a lithofacies scheme modified from Orme et al. (2015) for all deposits (Table 1). Samples for petrography and geochronology were collected within the context of the measured section and at four field stations (Supplementary Material I).

Sandstone modal analyses

Eleven samples of medium-grained sandstone were collected and cut for standard petrographic thin sections to determine their composition and interpret their provenance. Nine samples are from within the measured stratigraphic section and two from other field stations. All thin sections were stained for Ca-plagioclase and K-feldspar. Four-hundred and fifty framework grains were counted according to the Gazzi-Dickinson point-counting method (Gazzi, 1966; Dickinson, 1985). Grain types and modal parameters are defined in Table 2 and shown in Figure 5. Recalculated data are available in Supplementary Material II. Qt-F-L, and Lm-Lv-Ls ternary diagrams and petrographic classification of Garzanti (2016) are used for interpretation (Figure 6). Two samples (62518DA1_467 and 62518DA1_590) of red claystone from the measured section (Figure 3) were collected and cut for standard petrographic thin section to investigate their composition.

U-Pb detrital zircon geochronology: Provenance and Chronostratigraphy

We collected 10 medium-grained sandstones from the Dênggar region for detrital zircon U-Pb geochronology, including four new samples from field stations 1, 2, 6 and 8 (Figure 2) and six samples from the measured section, which were previously published in Laskowski et al. (2019). We analyzed all samples using laser ablation-multicollector-inductively coupled plasma-mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center following the methods and data reduction of Gehrels and Pecha (2014) and Pullen et al. (2018) (Supplementary Material III). Selected at random, a minimum of 300 grains per sample from the measured section and 100 grains per sample from four field stations were analyzed. Individual analyses of zircons have an analytical uncertainty of 1-2% for $^{206}Pb/^{238}U$, $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{204}Pb$ ages (2 σ level). For all samples, ^{204}Pb corrected $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages were used for grains less than and greater than 900 Ma, respectively. Uncertainties are at the 1 σ - level and include only measurement errors. One-σ weighted means of the FC, R33, and SL standards analyzed during data acquisition are 1096.93±3.16 Ma (MSWD = 0.88), 418.28±1.5 Ma (MSWD = 1.57), and 555.06±1.66 Ma (MSWD = 1.05) respectively. These compare with reference ages of 1099±2 Ma (Paces and Miller, 1993; Schmitz et al., 2003), 419.3±0.4 Ma (Black et al., 2004), and 563.5±2.3 Ma (Gehrels et al., 2008) respectively. Individual zircons with >20% discordance or >5% reverse discordance were not considered.

Kernel density estimate (KDE) plots were generated using DetritalPy (Sharman et al., 2018; Figure 7). Our chronostratigraphic age control comes from the youngest age population of detrital zircons from each sample. From these, we calculated maximum depositional ages (MDAs) using three techniques: age of the youngest single grain (YSG), weighted mean age of the youngest two grains or more that overlap at 1σ [YC1σ(2+)], and weighted mean age of the youngest three grains or more that overlap at 2σ [YC2σ(3+)] (Table 3). Dickinson and Geherls (2009) and Coutts et al. (2019) demonstrate that in various tectonic settings each of these methods is statistically robust and likely to yield accurate ages that are consistent with true depositional ages. However, we choose to only interpret MDAs calculated using the YC2σ(3+) method as this conservative method reduces the possibility of including single grains whose ages may result from Pb loss or field and laboratory contamination (Coutts et al., 2019).

RESULTS

Field Mapping

Three units were mapped within the field area based on field observations of lithology, structural position, and examination of previously published maps. Geochronological results (see below) confirm field correlations. From north to south, the mapped units include siliciclastic-matrix mélange (Ks), the Rongmawa Formation (Kr), and Tethyan Himalaya (TH) sedimentary rocks, undivided (Figure 2). Field mapping indicates that the Rongmawa Formation comprises at least one kilometer of intact section and likely three or four times that if there are no breaks in the section across river valleys (Figure 2). The Rongmawa Formation is bounded on all sides by moderately north-dipping reverse faults (Figure 2). We interpret that both faults are splays of the Zhongba-Gyangze thrust (Burg and Chen, 1984; Wang et al. 2017), which juxtaposes YSZ mélange against Tethyan Himalaya strata throughout southern Tibet (Ratschbacher et al., 1994; Ding et al., 2005). Rock descriptions keyed to field stations within each unit are included in the Sedimentology and Stratigraphy section, below.

Sedimentology and stratigraphy

Stratigraphic section DA1 is 1037 m thick, measured across a northward dipping homoclinal panel from the valley floor on the north side of a gully to the top of the ridge (Figures 2-4A). The section can be divided into three parts based on abrupt lithological changes. The lowermost 440 m comprise interbedded massive siltstone (Fsm) and very fine-medium-grained massive sandstone (Sm), and composite beds which fine upward from massive sandstone to plane-parallel laminated sandstone (Sm/Sh) (Figure 4B). A few medium-grained rippled sandstones (Sr) are found toward the top of this succession, as well as bioturbated siltstones (Figure 4C). Beds have non-erosional bases and are mostly between 5-10 cm thick with sandstone beds increasing in thickness up-section to 15-25 cm thick. A few sandstone beds fine-upward from medium-grained massive sandstone to fine-grained plane-parallel sandstone.

At 440 m, there is an abrupt lithologic change from interbedded sandstone and siltstone to green and red siltstone and claystone, which continues up-section for 300 m (Figure 4D). The first 15 m are massive green siltstone with 2-4 cm wide chert nodules (Figure 4E). Overlying this, in sharp contact are a series of 3-8 cm thick massive to faintly laminated red claystone beds (Fcl). Radiolaria are found in thin sections of the red claystones. The section alternates between red claystone (Figure 4F) and green siltstone for 300 m until an abrupt lithologic change at 732 m to massive sandstone interbedded with massive siltstone. At the transition, there is a 10 m thick succession of alternating thin sandstone and siltstone beds (<5 cm each), overlain by a series of 20-30 cm thick sandstones beds that fine upward from massive to horizontally laminated, separated by <3 cm thick massive siltstone intervals (Figure 4G). Bedding returns to alternating thin massive sandstone and siltstone beds (Sm/Sh; < 5 cm each) for 288 m (Figure 4H). The uppermost 17 m consist of 40-60 cm thick massive to horizontally laminated sandstone (Sm/Sh), with recessive siltstone intervals (Figure 4I). Within the uppermost 305 m, there are rare bioturbated siltstone intervals, similar to the bioturbated sandstones in the lowermost 440 m (Figure 4C).

From south to north, nine additional sedimentologic descriptions were conducted within mapped units (Figure 2). At field station 1, which we map as the Tethyan Himalaya Sequence, an outcrop just north of the Yarlung River consists of medium-grained massive sandstone with granule conglomerate lenses. The sandstone is quartz-rich in hand sample and there is abundant liesegang banding. A sandstone sample was collected for U-Pb geochronology. Field Stations 2-6 are mapped within the Rongmawa Formation. Outcrops at field stations 2 and 3 consist of fine-grained massive to horizontally laminated 10-20 cm thick sandstone beds (Sm/Sh) interbedded with green-grey siltstone (Fsm);

sandstones are quartz rich with unidentifiable lithics in hand-sample. Outcrops at stations 4 and 5 consist of fine-to-medium grained massive sandstone interbedded with green shale. Sandstone beds vary in thickness between 20-50 cm. Quartz, feldspar, white mica and lithics are present in hand-sample. At field station 5, horizontal burrows are present. Field station 6 consists of fine-to-medium grained massive sandstone and matrix-supported polymictic granule conglomerate beds interbedded with green to red siltstone. Sandstone beds consist of quartz, feldspar, chert and volcanic lithics in hand-sample. A sample for U-Pb geochronology was collected at this field station.

Field stations 7-9 are located within the siliciclastic-matrix mélange (Figure 2). Field stations 7 and 8 predominantly consist of blue-green phyllite with transposed bedding. At field station 8, a sandstone for U-Pb geochronology was collected from a well-cemented feldspathic block within the transposed phyllite matrix. Field station 9 consists of a succession of massive lithic-rich sandstone interweaved with green phyllite and serpentinite; the succession continues upslope for 100s of meters, beyond our mapping area.

Chronostratigraphy

Maximum depositional ages (MDAs) from detrital-zircon U-Pb age populations provide depositional age control for the Rongmawa Formation and neighboring stratigraphy in the Dênggar region. Table 3 presents three candidate MDAs for each sample, with our chosen YC2σ (3+) method in bold. Two new samples from the Rongmawa Formation yield Early and Late Cretaceous MDAs of 86.9±0.60 Ma (62418DA2) and 128.9±0.71 Ma (62518DA3). These are similar to the range of the MDAs from the measured section (88.7±0.65 Ma to 125.2±0.64 Ma; Laskowski et al. 2019). Sample 62418DA2 is slightly younger than the youngest MDA from within the measured stratigraphic section (88.7±0.65 Ma), consistent with its position up-section. The samples from the siliciclastic matrix mélange and Tethyan Himalaya yield a MDAs of 90.2±0.61 Ma and 504.2±1.32 Ma, respectively. Samples from the Rongmawa Formation overlap in age with the ~ 90 Ma MDA from a block within the siliciclastic matrix mélange.

Provenance: Sandstone Petrography and zircon U-Pb geochronology

The modal framework composition of 11 sandstone samples from the Dênggar region are shown in four ternary diagrams in Figure 6 and recalculated modal values are given in Supplementary Material II. Framework grains are summarized in Table 2. Quartzose grains include monocrystalline quartz (Qm) and polycrystalline quartz (Qp), with both showing undulatory extinction (Figure 5). Volcanic lithic grains are abundant and predominantly consist of vitric, lathwork and microlitic textures. Sedimentary lithic grains include chert, siltstone and mudrock. Feldspar varieties include a few plagioclase feldspar (P), but potassium feldspar (K) is absent. Accessory minerals include biotite, white mica, chlorite, epidote, hornblende and zircon. Nine samples are litho-quartzose and two are quartzo-lithic following the classification scheme of Garzanti (2016) (Figure 6).

From the four new geochronologic samples, a total of 381 zircon grains yielded ages with acceptable precision and concordance for geologic interpretation (Figure 7). Sample 62518DA4 from what we mapped as Tethyan Himalaya yields age >450 Ma, with age peaks at ~ 500 Ma, 800-1200 Ma, and a few grains >1500 Ma. Two samples from the Rongmawa Formation (62418DA2 and 62518DA3) yield Mesozoic age population peaks of ~ 90 Ma, ~125 Ma and ~ 200 Ma and pre-Mesozoic age ages of ~ 500 Ma, ~ 800-1200 Ma and a tail of ages >1500 Ma. The age spectra from these two samples are consistent with the six samples collected within stratigraphic section DA1, with each sample dates at n > 300 grains. A composite of these samples (n = 1716) highlights Mesozoic age population peaks at ~90-100 Ma, ~125-145 Ma, ~175-220 Ma (Figure 7). Sample 62518DA3 (n = 96) contains two Cretaceous single-grain ages of 66.3 ± 1.0 and 74.6 ± 0.9 Ma. However, these are not included in our interpretations as they are significantly younger than Rongmawa samples where >300 grains were dated and they do not overlap within error of other grains from the sample. Therefore, we consider these grains be the result of Pb-loss or contamination in the laboratory or field. Sample 62618DA1_mg, collected within the siliciclastic matrix mélange, is similar to all Rongmawa samples. The age spectra (Figure 7) reveals a ~ 90 Ma age peak, a scattering of grains between ~125-150 Ma, and a peak from ~200-220 Ma.

DISCUSSION

Depositional Setting and Age of the Rongmawa Formation

Lithofacies in stratigraphic section DA1 are consistent with deposition by low- and high-density turbidity currents and suspension settling of pelagic detritus in a deep-marine setting. Within the lowermost 400 m, the fine grain size, sharp base and thin bed thickness, normal grading (Sm/Sh), and abundance of interbedded siltstone and claystone suggest deposition by low-density turbidity currents (Figure 3 and 4; Bouma, 1962; Mutti, 1992). Lithofacies Sm, Sh, Sr and Fsm can be thought of as Ta, Tb, Tc and Td within the turbidite classification scheme of Bouma (1962). The graded beds reflect suspension settling during waning flow conditions and planar laminations represent internal divisions of low-density turbidities (Bouma, 1962). Structureless sandstones (Sm) were likely deposited by high-density turbidity flows (i.e., S3 sensu Lowe, 1982). We interpret the interval of green siltstone and red laminated claystone (Fcl) to be deposited by suspension settling of biogenic silica (Figure 4). This is supported by the presence of radiolaria within thin sections of red claystone, as well as the absence of clastic material. In the uppermost 300 m, lithofacies Sm and Sm/Sh are interpreted to reflect deposition by traction carpet and the transition from traction carpet to suspension settling deposition during turbidity flows, respectively (Figure 3 and 4; Bouma, 1962; Lowe 1982; Mutti, 1992). Field stations 2-6 consist of similar lithofacies (Sm, Sm/Sh, Fsm) and are interpreted to be deposited by turbidity currents.

Our new and previously published U-Pb detrital zircon MDAs constrain the stratigraphy of section DA1 and field stations 2-6 to be deposited ca. 92-87 Ma (Figure 7; Table 3). Samples with Early Cretaceous MDAs are interwoven with younger Late Cretaceous samples. Therefore, we interpret that all of the stratigraphy found in the Dênggar region was deposited in the Late Cretaceous, ca. 92-87 Ma. This is consistent with previous depositional age estimates for the Rongmawa Formation near Ngamring (Figure 1). We interpret the MDAs as approximating true depositional age due to activity of the Gangdese magmatic arc during this time interval and presence of syn-depositional grains in nearby forearc deposits, which are consistent with dates from interbedded tuffs (e.g., Orme et al. 2015). In addition, younger, syn-collisional trench strata such as the succession preserved at Sangdanlin contain syn-collisional zircons, which are not present in the Rongmawa Formation (e.g., DeCelles et al. 2014). In the Dênggar region, the structural position and age of the Rongmawa Formation relative to the siliciclastic-matrix mélange is identical to that near Ngamring. Specifically, the turbiditic upper member of the Rongmawa Formation near Ngamring is in fault contact with the siliciclastic-matrix mélange to its north, with both south of the Xigaze forearc basin (Cai et al., 2012; this study). Similarly, the Rongmawa at Dênggar and the trench basin strata of the Jiachala Formation near Xigaze are in contact with Tethyan Himalayan units to the south. In addition, MDAs from the Rongmawa Formation overlap with the MDA from the siliciclastic mélange (62518DA1_mg), suggesting they are genetically related and deposited during the same time interval.

Based on the sedimentology, structural position, and MDAs, we interpret the Rongmawa Formation in the Dênggar region to be deposited in a trench basin setting during Late Cretaceous time. The presence of turbidites and deposition of suspension settling of biogenic silica indicate marine deposition. The turbidites were likely generated from slumping, although we note lack of large mass transport deposits in the area; notably, olistoliths are found in both the Jiachala and Luogangcuo Formations (An et al. 2018; Fu et al. 2018). Moore and Karig (1976) suggest the absence of slumping of accretionary material depends on the balance between sedimentation rate and the rate of motion on thrusts of the inner wedge. In their model, if the sediment supply is high, this promotes the development of a cover of slope sediments across the wedge, prohibiting the exposure of the accretionary complex and subduing slumping and production of debris flows.

Provenance of Cretaceous Trench Basins

The modal sandstone compositions of the Rongmawa Formation near Dênggar (Figure 1) are predominantly litho-quartzose (Garzanti, 2016) and plot within the recycled orogen field of Dickinson et al. (1983). These samples are similar to the composition of sandstones from the Rongmawa Formation near Ngamring >130 km east (Figure 1), which plot within the recycled orogen and continental block fields (Figure 6; Cai et al., 2012; Metcalf and Kapp, 2019). However, samples from each study area group slightly differently, dependent on plagioclase feldspar and lithic content. Notably, all samples from the Rongmawa Formation across the YSZ have little to no K-feldspar (<0.02%). Similarly, sandstones from trench basin strata of the Jiachala Formation are mostly litho-feldspatho-quartzose to feldspatho-litho-quartzose volcaniclastic, and plot within the recycled orogen field (Figure 6; Fu et al. 2018). By contrast, turbiditic sandstones from the Luogangcuo Formation, which was also deposited during Late Cretaceous time near Saga (Figure 1), are feldspatho-quartzo-lithic volcaniclastic and plot primarily within the magmatic arc field (Figure 7; An et al. 2018). The Luogangcuo Formation contains both plagioclase and K-feldspar, but K-feldspar is limited (< 0.1%).

The Mesozoic age-probability peaks of ~ 90-100 Ma, ~125-145 Ma and ~ 200-220 Ma and pre-Mesozoic ages from Rongmawa Formation and siliciclastic-matrix mélange at Dênggar are consistent with derivation from the Gangdese magmatic arc and Lhasa terrane (Figure 7). This age spectrum is consistent with previous studies on the Rongmawa Formation near Lazi and Ngamring (Cai et al., 2012; Metcalf and Kapp, 2019) and the Jiachala Formation southeast of Xigaze (e.g., Fu et al., 2018). In addition, the age-probability peaks are similar to the Xigaze forearc basin to the north, with the notable exception of the ~ 200-220 Ma age population, which is absent in the Saga region and limited in the Lazi region to the east (Figure 1 and 7). Laskowski et al. (2019) document that the ~200-220 Ma age-probability peaks found in Dênggar are rare in the Lhasa terrane, except for near Lhasa city where similar Hf isotopic compositions and U-Pb ages are preserved. Therefore, Laskowski et al. (2019) interpret the source of this age peak to be derived from the central-eastern Lhasa terrane near Lhasa and suggest there was a Cretaceous sediment dispersal system that must have bypassed much of the forearc basin and transported detritus axially parallel to the trench from Lhasa to Dênggar. Our sandstone modal petrographic results support the interpretation that the Rongmawa Formation samples are derived from a similar source region based on their recycled orogen provenance field and detrital zircon age spectra (Figure 6 and 7). By contrast, the Xigaze forearc basin and Luogangcuo Formation near Saga, are primarily derived from more proximal Cretaceous igneous rocks of the Gangdese magmatic arc based on the abundance of volcanic lithics within sandstone samples (Orme et al., 2015; An et al. 2018). Therefore, the Luogangcuo Formation is interpreted to be derived from an overfilled Xigaze forearc basin (An et al. 2018).

We present a model wherein the Cretaceous subduction trench received detritus from an axial sediment dispersal system that transported sediment from headwaters in the central-southern Lhasa terrane near Lhasa City directly to the trench and then flowed westward parallel to the trench, depositing detritus in trench basins near Xigaze (Fu et al., 2018), Ngamring (Cai et al. 2012; Metcalf and Kapp, 2019) and as far west as Dênggar (Figure 8; Laskowski et al., 2019; this study). This is supported by the ~200-220 Ma detrital zircon population and more quartz-rich sandstones of trench deposits compared with lithic-rich sandstones devoid of or limited in this detrital zircon population within the Xigaze forearc basin (Figure 7). By contrast, the lithic-rich Luogangcuo Formation was likely deposited on the slopes of the subduction complex, deriving its detritus from transverse drainage systems with headwaters in the Gangdese magmatic arc and Xigaze forearc basin to the north (An et al. 2018). This interpretation implies the Xigaze forearc basin in the Saga region to be overfilled at this time (An et al. 2018) and sediment to be trapped within the wedge-top basins of the subduction complex, prohibiting substantial amounts of volcanic-rich detritus to reach the trench (Figure 8). However, the forearc must have been underfilled in other parts of the basin, as its sediments were not the primary source for other trench basin strata. This implies that parts of the forearc basin were likely segmented from each other, rather than forming a well-integrated basin system.

Integration with Regional Tectonics

Global summaries of convergent margin tectonics identify two behavioral modes: trench advance accompanied by subduction erosion and accretion sometimes accompanied by trench retreat (von Heune and Scholl, 1991; Clift and Vannucchi, 2004). Preservation of trench basin strata deposited during Late Cretaceous time along the southern Lhasa terrane compared with the lack of trench deposits prior to ~ 92 Ma and after ~ 80 Ma (Metcalf and Kapp, 2019) suggests the margin experienced a period of significant accretion during this interval. Across the YSZ, trench basin strata of the Rongmawa, Luogangcuo and Jiachala formations were deposited between ~92 and ~80 Ma and were likely accreted shortly thereafter. Modern convergent margins tend to exhibit accretionary behavior when convergence rates are less than

76 mm yr−1 and/or trench sediment thicknesses are >1 km. Conversely, they exhibit erosive or non-accretionary behavior when rates are faster than 60 mm yr−1 and/or trench sediment thicknesses are <1 km (Clift and Vannucchi, 2004). If these criteria apply to the Late Cretaceous Eurasian margin, then it is likely that increased convergence and/or sediment supply led to widespread accretion. There is major disagreement about the India-Eurasia convergence rate between ~90 and ~80 Ma. The reconstruction of van Hinsbergen et al. (2011) involves steady ~50 mm/yr convergence between 120 and 90 Ma followed by a rapid increase to ~140 mm/yr at 90 Ma. By 80 Ma, convergence drops back down to ~80 mm/yr. As increased convergence is expected to favor erosive behavior, the timing of accretion at ~ 92-80 Ma is apparently at odds with this reconstruction. The reconstruction of Gibbons et al. (2015) involves convergence rates between 65 and 80 mm/yr from 120 to 90 Ma followed by a decline to ~50 mm/yr at ~85 Ma. At ~80 Ma, convergence rapidly increases to 120 mm/yr then drops down to 80 mm/yr by ~75 Ma. It is plausible that the decline in convergence rate at 85 Ma led to contemporaneous accretion of trench basin strata while the subsequent increase at ~80 Ma prohibited further accretion. In the absence of a sediment supply driver, the reconstruction of Gibbons et al. (2015) provides a more compelling explanation for accretion than the van Hinsbergen et al. (2011) reconstruction.

An alternative possibility is that sediment supply controlled the timing of accretion of trench basin strata. There are several tectonic drivers that might have increased sediment supply to the trench during Late Cretaceous time. As the hypothesized sediment supply increase corresponds in time with Late Cretaceous adakitic magmatism and granulite facies metamorphism (the “tectono-thermal event”) in the southern Lhasa Terrane (Kapp and DeCelles, 2019), it is possible that they are interrelated. In the traditional explanation, the “tectono-thermal event” is attributed to Neo-Tethyan oceanic ridge subduction. In modern Costa Rica, subduction of the Cocos Ridge at the Middle America Trench drives rapid subduction erosion, evidenced by intervals of extreme (~1200 m), short-duration (~2 Myr) subsidence in the forearc region (Vannucchi et al., 2013). If a similar process occurred in southeast Tibet associated with Neo-Tethyan oceanic ridge subduction, it might have created a pathway for putative rivers such as the Ancestral Lhasa River (Laskowski et al., 2019) to transport sediment directly to the trench. The fact that Xigaze forearc basin is mainly confined to a ~500 km wide swath of the central YSZ between Zhongba and ~ 90 km east of Xigaze (Figure 1) leaves open the possibility that subduction erosion destroyed some segments of the forearc basin in southern Tibet, creating unobstructed transport pathways to the trench in these areas.

The alternative explanation for the Late Cretaceous “tectono-thermal event” in southern Tibet involves trench retreat and opening of the hypothesized Xigaze back-arc basin (Figure 1; Kapp and DeCelles, 2019). In this scenario, steepening subduction (i.e. slab rollback) of the Neo-Tethyan oceanic slab is expected to result in decreased coupling with forearc lithosphere. Decreased coupling might have led to exhumation in the forearc region, which would in turn lead to increased sediment supply to the trench. The provenance of trench basin strata is one test of this explanation. This study and previous studies (Cai et al., 2012; Fu et al., 2018; An et al., 2018; Laskowski et al., 2019) interpret that trench basin strata were derived from the Lhasa terrane. Differences between contemporaneous trench basin and Xigaze forearc basin detrital zircon age spectra (Laskowski et al., 2019; this study) imply that trench basin sediments were not recycled from the forearc basin. Therefore, if the southern part of the Gangdese magmatic arc rifted from Eurasia during Late Cretaceous time to open the Xigaze backarc basin (Kapp and DeCelles, 2019), the requisite sources for the Rongmawa Formation must have been included in the rifted continental fragment. The most distinctive of these sources are the Upper Triassic plutons and volcanic rocks that are mainly preserved near Lhasa city in southeast Tibet (Figures 1 and 8; Laskowski et al., 2019).

CONCLUSIONS

The Rongmawa Formation near Dênggar, Tibet was deposited between ~92-87 Ma in a deep-marine, trench basin setting by turbidity currents and suspension settling of pelagic detritus. Provenance analyses are consistent with an axial sediment dispersal system that was sourced in the central-southern Lhasa Terrane near Lhasa City and transported detritus westward parallel to the trench. Accumulation of trench basin strata deposited near Xigaze, Ngamring, Dênggar, and Saga between ~ 92-80 Ma suggest the margin was accretionary during this time interval. It is plausible that a period of decreased convergence at ~ 90-85 Ma, followed by a period of increased convergence after ~ 80 Ma may have promoted trench sediment accumulation and subsequent erosion, respectively. This period of accretion may be linked to the subduction of an oceanic ridge, which may provide a mechanism to erode parts of the Xigaze forearc basin and promote increased sediment delivery directly to the trench. In addition, this study requires tectonic scenarios that invoke back-arc extension during deposition of the Rongmawa Formation to include the requisite sources within rifted continental fragments.

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FIGURE CAPTIONS

Figure 1: Simplified geologic map of the southern Tibetan Plateau and northern Himalaya ca. 80°E to 92°E, modified from Pan et al. 2004 and Zhu et al. 2011. The YSZ is defined by the siliciclastic and ophiolitic mélange, shown in blue and grey, respectively. The Xigaze forearc (green) and is limited to ~ 500 km of the central part of the suture zone. Lower Jurassic-Upper Triassic igneous rocks (purple) are restricted to areas near Lhasa City. YSZ-Yarlung Suture Zone; ISZ-Indus Suture Zone; GCT-Great Counter Thrust; STF-South Tibet Fault; MCT-Main Central Thrust; MBT-Main Boundary Thrust; MFT-Main Frontal Thrust. The geologic map in Figure 2 is located near the placemark for Dênggar.

Figure 2: Geologic map of the Dênggar area with all DZ and thin section sample localities. Topographic contours (50 m interval) generated from 3 arc sec Shuttle Radar Topography Mission data. "Dênggar Section" shown in Figure 3 and numbers within square polygons are Field Stations 1-9.

Figure 3: Measured stratigraphic section (in meters) of the Rongmawa Formation at Dênggar. See Figure 2 for location of measured section and Table 1 for further explanation of lithofacies codes.

Figure 4: Photographs of the Rongmawa Formation lithofacies within the Dênggar section shown in Figure 3; lithofacies defined in Table 1. (A) Panoramic photographic of the measured section, viewed from the southeast. Up-section is to the right (north) and electrical poles in the central part of the photograph provide scale. (B) Interbedded Sm or Sm/Sh (5-10 cm thick) and Fsm at the base of the section; 1.5 m Jacob Staff for scale. (C) Bioturbated siltstone at 167 m. (D) Abrupt lithology change at 440 m to green Fsm and red claystone (Fcl), viewed from the southwest. (E) Green Fsm with 2-4 cm wide chert nodules. (F) Faintly laminated red claystone beds (Fcl; <5 cm each); 1.5 m Jacob Staff for

scale. (G) 20-30 cm thick Sm or Sm/Sh beds interbedded with Fsm found at 732 m. (H) 5-10 cm thick Sm beds interbedded with massive Fsm at 920 m; camera lens in middle of photograph for scale. (I) 40-60 cm thick Sm/Sh beds interbedded with Fsm at 1032 m; 1.5 m Jacob Staff for scale.

Figure 5: Photomicrographs of litho-**quartzose** and quartzo-**lithic** petrofacies from within the measured section shown in Figure 3, following the classification scheme of Garzanti (2016). (A, B): XPL (A) and PPL (B) photomicrographs of litho-**quartzose** petrofacies. (C) litho-**quartzose** petrofacies with a rare plagioclase feldspar present. (D) Quartzo**-lithic** petrofacies. (E) litho-**quartzose** petrofacies with secondary calcite. (F) litho-**quartzose** petrofacies with accessory biotite and secondary calcite veins. Qm-monocrystalline quartz; V-volcanic (all varieties); P-Plagioclase feldspar; Cal-calcite; Bt-biotite.

Figure 6: Ternary diagrams showing composition of sandstones from the Rongmawa Formation at Dênggar. See Figure 3 for sample locations. (A) Petrographic classification from Garzanti (2016); bold font indicates dominant end-member with Q-quartz, F-feldspar and L-lithic. (B) Provenance subfields from Dickinson et al. (1983) with CB-Cratonic block, MA-magmatic arc, and RO-Recycled orogen. (C) Lithic specific: Lv-volcanic, Lm-metamorphic, Ls-sedimentary. (D) Feldspar specific: Qm-monocrystalline quartz, P-Plagioclase feldspar, K-Potassium feldspar.

Figure 7: Detrital zircon age spectra of new Dênggar samples and composite of six in-section samples from Laskowski et al. (2019), arranged north to south, composite Xigaze forearc basin age spectrum from Orme et al. (2014) and Orme and Laskowski (2016), trench basin strata from Metcalf and Kapp (2019), Cai et al. (2012), and Fu et al. (2018). Plots are kernel density estimates (KDEs) generated with

two-million-year bandwidth for 0-250 Ma range and ten-million-year bandwidth for 0-3000 Ma range in *DetritalPy* (Sharman et al., 2018).

Figure 8: Schematic paleogeographic reconstruction of the southern Asian margin ca. 90 Ma illustrating the interpreted axial-transport of detritus from Jurassic and Triassic plutons near Lhasa City parallel to the trench toward Dênggar. In contrast, the Xigaze forearc basin and proximal parts of the subduction complex were sourced primarily from transverse drainages with headwaters in the Cretaceous Gangdese magmatic arc. Schematic includes the proposed location of an oceanic ridge to explain the lack of forearc basin strata preserved east of Lhasa.

TABLE CAPTIONS

Table 1: Lithofacies used in this study [after Orme et al. (2015)]

Table 2: Modal point counting parameters

Table 3: Detrital zircon maximum depositional ages (MDAs) with 1σ calculated errors, mean square of weighted deviates and cluster sizes for all detrital zircon U-Pb samples. MDAs were calculated using *DetritalPy* (Sharman et al., 2018) using three techniques: age of the youngest single grain (YSG), weighted mean age of a minimum of the youngest two grains that overlap at 1σ [YC1σ(2+)], and weighted mean age of a minimum of the youngest three grains or more that overlap at 2σ [YC2σ(3+)].

SUPPLEMENTARY MATERIAL

Supplementary Material I: Sample locations

Supplementary Material II: Recalculated modal petrographic data

Supplementary Material III: U-Pb detrital zircon geochronologic data