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Provenance Analysis of Cretaceous Peripheral Foreland Basin in Central Tibet: Implications to Precise Timing on the Initial Lhasa-Qiangtang Collision

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Abstract

Mesozoic strata along northern margin of the Lhasa terrane near Dingqing, Tibet provide a semi-continuous record of the Bangong-Nujiang Ocean closure and the subsequent Lhasa-Qiangtang collision. In this study, we present results of sandstone petrographic, detrital zircon U-Pb, and Cr-spinel geochemical data to determine the provenance of the Mesozoic strata (from the Triassic Quehala Group and the Mid-Jurassic to Lower Cretaceous Xihu, Lagongtang, and Duoni

Formations, which are young from ~220 Ma to ~100 Ma) in this region, thereby allowing for interpretation of their tectonic setting. The similar 1200-900 age cluster from the lower Xihu Formation to that of the Triassic Quehala Group and the distinct age peaks at ~200 Ma and ~146 Ma from the upper Xihu Formation suggest a Lhasa terrane provenance to the south. Distinctive age clusters of 300-210 Ma and ~1800 Ma and Cr-spinel composition analysis of the Lagongtang Formation indicate a provenance shift from the Lhasa terrane to the Qiangtang terrane and the Bangong-Nujiang suture zone to the north. The Lagongtang Formation was deposited in a bathyal-abyssal to shallow-slope environment from north to south, that we interpret as the foredeep depozone and distal foredeep of a peripheral foreland basin system that developed due to flexural subsidence related to the Lhasa-Qiangtang collision and terrane accretion. The age of the Lhasa-Qiangtang collision is constrained by a ~140 Ma tuffite U-Pb age at the base of the foreland basin strata. An angular unconformity between the Xihu and Lagongtang Formation, which we interpret as the result of the Lhasa-Qiangtang collision. Our results indicate that the Lhasa-Qiangtang collision initiated around ~140 Ma in the Dingqing region, simultaneously with previous determinations 1200 km to the west near Gaize area. Therefore, we prefer quasi-simultaneous onset of collision along-strike to zippering collision models wherein the east collision age is older than the west.

Keywords： Tibetan Plateau; Bangong-Nujiang Suture Zone; Lhasa-Qiangtang Collision; Foreland Basin; Provenance Analysis; Collisional tectonics.

1. Introduction

Long before the Cenozoic India-Asia collision and formation of the Tibetan Plateau and

Himalayan orogen, sequential amalgamation of several continental terranes occurred beginning in Paleozoic time. These successive accretion events pre-conditioned the Eurasian margin by forming the Proto-Tibetan Plateau (Kapp et al., 2005; 2007; Wang et al., 2014; Pan et al., 2012; Ding et al., 2014; Kapp and DeCelles, 2019). Determining the timing of terrane accretion and attributing the regional stratigraphic units and deformation events to these events aids our broader understanding of the development of the Tibetan Plateau, the prototypical example of an active collisional orogen. The Lhasa and Qiangtang terranes, formerly separated by the Bangong-Nujiang Ocean (BNO) (also refer as Meso-Tethyan ocean), are the most prominent crustal fragments by area in the central Tibetan Plateau. The Mesozoic BNO formerly separated the Qiangtang terrane to the north from the Lhasa terrane to the south, persisting for approximately 100 Myr (Yin and Harrison, 2000; Liu et al., 2018) and its final closure resulted in the Lhasa-Qiangtang collision. This was the final terrane accretion event prior to the onset of Himalayan-Tibetan orogenesis. The precise timing of the initial Lhasa-Qiangtang collision is still debated, with inferred ages ranging from Middle Jurassic (Pan et al., 1983; Xu et al., 1985; Ma et al., 2017), to Late Jurassic-Early Cretaceous (Yin and Harrison, 2000; Zhang et al., 2014; Zhu et al., 2016), and even as late as Late Cretaceous (Li et al., 2014; Zhang et al., 2012; Fan et al., 2018). These previous estimates were based on the Middle Jurassic low-grade metamorphism, Late Jurassic unconformity above the accretionary complex or magmatic rocks, and Early Cretaceous Ocean Island Basalt, respectively. The precise determination of the collision age along the Bangong-Nujiang suture zone (BNSZ) will determine whether the Lhasa-Qiangtang collision initiated synchronously (Zhang et al., 2012, 2014; Wang et al., 2016) or diachronously in a scissor-like fashion wherein the onset age becomes younger to the west (Yin and Harrison, 2000; Pan et al., 2004; Zhu et al., 2013; Yan et al., 2016).

We interpret that the broad range of previously published initial Lhasa-Qiangtang collision ages can be ascribed to the adoption of different approaches or different comprehensions of the term “initial continental collision”. The timing of subduction-related magmatism (Li et al., 2014; Liu et al., 2018), metamorphism (Xu et al., 1985), paleomagnetic closure (Yan et al., 2016; Ma et al., 2018b; Cao et al., 2019), crustal shortening (Murphy et al., 1997; Kapp et al., 2007), and BNSZ ophiolite emplacement ages (Zhu et al., 2006; Wang et al., 2016) have all been used to determine the timing of the initial Lhasa-Qiangtang collision. Comparatively few studies have focused on sedimentary records deposited along the northernmost margin of the Lhasa terrane (Leier, 2005, 2007; Kapp et al., 2007; Zhang et al., 2014), and this method is widely used an acceptable in the context of constraining the India-Asia collision time (e.g. DeCelles et al., 2014; Ding et al., 2016; Baral et al., 2019). Here we define the age of collision onset at the oldest age of sedimentary overlap between strata derived in part from the Qiangtang terrane and the northern Lhasa terrane.

In the Dingqing area, eastern segment of the BNSZ, a semi-continuous Mesozoic sedimentary succession exposed along the northernmost margin of the Lhasa terrane. In this study, we present a new dataset of petrography, detrital zircon U-Pb geochronology and Cr-spinel compositions from the Mesozoic sedimentary sequences (the Late Triassic Quehala Group, the Middle-Late Jurassic Xihu Formation, the Early Cretaceous Lagongtang Formation, and the Early-Late Cretaceous Duoni Formation (see Supplementary Tables S1-S3 for details)). This contribution allows us to reconstruct the precise timing of final closure of the BNO and the subsequent initial Lhasa-Qiangtang collision. The data are mainly from the newly-ascribed peripheral foreland basin strata (Lagongtang and Duoni Formations) that unconformably overlie passive margin strata of the northern Lhasa terrane (the Quehala Group and Xihu Formation). In addition, this is the first determination of the collision age from the eastern segment of the BNSZ (Fig. 1), and a complete comparison with previous results from central and western parts of the BNSZ (e.g. Ma et al., 2017, 2018a; Li et al., 2017a, 2017b).

2. Geological setting

The Tibetan Plateau, from south to north, is composed of five main continental terranes: The Tibetan Himalaya, Lhasa, Qiangtang, Songpan-Ganzi and Kunlun, which are separated by the Indus-Yarlung Zangbo suture zone, the BNSZ, the Jinsha suture zone, and the Kunlun suture zone, respectively (Yin and Harrison, 2000; Kapp and DeCelles, 2019) (Fig. 1a). Our study area is located in the Dingqing county along eastern segment of the BNSZ that includes from north to south the following lithotectonic units: Qiangtang terrane, BNSZ and Lhasa terrane (Fig. 1b). Tectonic and stratigraphic divisions are specifically described as below.

2.1. Qiangtang Terrane

The Qiangtang terrane is further subdivided into the southern and northern Qiangtang terranes by the Triassic Longmo Co-Shuanghu suture, which is marked by the central Qiangtang metamorphic belt (BGMRXAR, 1993; Pan et al., 2004; Li et al., 2009). The southern Qiangtang terrane consists of the Neoproterozoic highly deformed metasedimentary crystalline basement rocks (Jitang and Gemuri Group), intruded by 476-471 Ma orthogenesis (Pullen et al., 2011). The Ordovician-Devonian limestone sequence, deposited on a stable carbonate platform in a continental margin setting, was covered by the Upper Carboniferous to the Middle Permian sedimentary rocks that containing abundant glacio-marine diamictites and basalt interlayers (Li et al., 2009). The Upper Paleozoic strata are conformably overlain by shallow shelf facies of Triassic strata (Riganpeicuo Formation) (BGMRXAR, 1993; Hou et al., 2018). Subsequent Jurassic to Early Cretaceous units include Upper Jurassic sandstones and limestone (Amdo Formation) intruded by 180-150 Ma granitoids (BGMRXAR, 1993), Middle Jurassic shales and sandstones intercalated with limestone (Sewa, Shaqiaomu and Jiebuqu Formation) (BGMRXAR, 1993). These sedimentary sequences rest on the Cretaceous terrestrial molasses deposits (Abushan Formation) by an angular unconformably (BGMRXAR, 1993).

2.2. Bangong-Nujiang Suture Zone

The Bangong-Nujiang suture zone is an important tectonic unit dividing the Qiangtang terrane to the north and the Lhasa terrane to the south in central Tibet, and is further subdivided into the western (Bangong Lake-Gaize), the middle (Dongqiao-Amdo), and the eastern (Dingqing-Nujiang) segments (Pan et al., 2012). Moreover, the BNSZ extends westwards for over 2000 km, represents remnants of the BNO, and therefore records crucial information about evolution of the BNO (Allègre et al., 1984; Yin and Harrison, 2000; Kapp et al., 2007; Zhu et al., 2016; Fig. 1a, b).

The accretionary complex (Mugagangri Group) mainly consists of deformed deep-sea turbidites containing dismembered ophiolitic fragments (Kapp et al., 2005; Pan et al., 2004). Those ophiolite fragments include mid-ocean ridge basalts (MORB-type), supra-subduction zone (SSZ-type) ophiolites (Wang et al., 2016), oceanic island-seamount basalts (Zhu et al., 2006, 2013). In addition, Wang et al (2016) suggests that Early-Middle Jurassic intra-oceanic subduction-related eruptions of SSZ-related lavas (ca. 190-164 Ma), followed by OIB-type (Ocean island basalts) mafic magmatism during the Early Cretaceous (ca. 132-108 Ma). A regional unconformity exists between the accretionary complex and the overlying strata (Girardeau, 1984; Yin and Harrison, 2000; Deng et al., 2017; Li et al., 2017a; Ma et al., 2017; Fig. 1b).

2.3. Lhasa Terrane

The Lhasa terrane is divided into northern, central and southern subterranes by the Shiquan River-Nam Co Mélange Zone and the Luobadui-Milashan Fault (Zhu et al., 2013). The northern Lhasa terrane is composed of chemically juvenile crust (Zhu et al., 2011a) covered by Middle Triassic-Cretaceous sedimentary sequences with abundant Early Cretaceous volcanic rocks and associated granitoids (Pan et al., 2004; Zhu et al., 2016). The central Lhasa terrane mainly consists of a Precambrian basement (Allègre et al., 1984), a Carboniferous-Permian metasedimentary sequence and the volcano-sedimentary sequence (Zhu et al., 2016). The southern Lhasa terrane is characterized by the Mesozoic-Tertiary Gangdese batholith (BGMRXAR, 1993) and associated Jurassic-Paleogene volcanic sequences (Zhu et al., 2008, 2016).

3. Stratigraphy of the northern Lhasa terrane and Sampling

The Mesozoic sequence exposed along the BNSZ in Dingqing area consists of upper Triassic-upper Cretaceous marine to terrestrial deposits (Fig. 1b, 2). The BNSZ is bounded by the Qiuzongma-Xuelashan-Zhuajinzha Fault to the north and the Quehala-Suruka Fault to the south (BGMRXAR, 2014b; Fig. 1e). The Mesozoic sequence in Lhasa terrane composed of, from oldest to youngest, the Quehala Group, the Xihu Formation, the Lagongtang Formation, and the Duoni Formation (Fig. 1c-f, 2).

The Quehala Group is juxtaposed against the coarse-clastic wedge-top strata of the Jingzhushan Formation across a thrust fault. In addition, it is in unconformable contact with the Xihu Formation to the south (Fig. 1c, e, 2, 3a). In stratigraphic section Ms-1 near Shagong town (Fig. 1e, Fig. 5): the lower Quehala Group is dominated by grey dolomitic limestone intercalated with thin bedded fine sandstone; the middle part is dominated by alternating beds of limestone and grey-black medium-fine quartz-sandstone or siliceous mudstone, some fossils were found in the limestone; the upper part is mainly composed of massive black mudstones with sandstone or limestone, which are lenticular in shape and of varying scales. The total thickness of the Quehala Group is ~320 m based on our measured sections. Limestone with terrestrial clastic rocks was deposited in subtidal low-energy zone, and alternating beds of limestone and fine quartz-sandstone was formed in mixed siliciclastic-carbonate system (Flügel, 2010; BGMRXAR, 2014b), while mudstone intercalated lenticular sandstone or limestone represents the continental shelf slope environment (Mutti, 1992; BGMRXAR, 2014b). These strata contain madrepore (*Thamnasteria rectilamellosa* Winker) and bivalve fossils (*Myophpria elegans* and Halobiidae) that suggest a Late Triassic depositional age (BGMRXAR, 2014b). Sandstone samples 2019TFD23 (n=1) and 2017TF55-49 (n=7) were collected from the lower and upper part of this group, respectively (Fig. 2, 5).

The Xihu Formation is in fault contact with Mugagangri Group to the north (Fig. 1c) and sits unconformably atop Triassic Quehala Group strata (Fig. 1c, 2, 3a). In the Ms-1 section near Shagong town (Fig. 1e, 5), Xihu Formation is composed of gray-black carbonaceous mud shale and lenticular medium-fine sandstone (Fig. 3b). Lenticular sandstone beds are common, with convex-down geometries, small scale, laterally extension of 3-8 m, maximum thickness of 5-20 cm, and shaly beds were found to contains plant debris and rich in organic matter. Massive organic-rich mud shale with minor small lenticular sandstones from the section Ms-1 were deposited in a prodelta setting (Pulham, 1989; Zhou and Zhang, 2009). At the base of the MS-1 section a ~20 m thick basal conglomerate is exposed, consisting of gravel-sized limestone clasts interbedded with a minor sandstone (Fig. 3a). Total thickness of the lower Xihu Formation in section Ms-1 is ~100 m. The upper Xihu Formation was studied in section Ms-2 near Gayouka town, consisting mainly of interbedded gray, medium-fine-silt sandstones of varying bed thicknesses with common parallel lamination and occasional ripple marks (Fig.6). Those fined-grained sandstones with ripple marks and parallel lamination were formed in shallow marine sedimentary environment (Zhou and Zhang, 2009). The upper Xihu Formation in section Ms-2 is ~50 m. Sporopollen (Perishinctidae) and ammonoid (*Virgatosphinctes* sp.) fossils suggests a Middle to Late Jurassic age for this formation (BGMRXAR, 2014b), and our detrital zircon data (Fig.4; Table 1; Supplementary Tables S1) from the upper part yield a well-constrained maximum depositional age of ~146 Ma based on YC1σ (3+) [weighted mean age (±1σ incorporating both internal analytical error and external systematic error) of youngest cluster of three or more grain ages] technique (Dickinson and Gehrels, 2009; Table 1). Three (2019TFD25/26/28) and four (2019TFD53/54/55/56) sandstone samples were collected from the lower (Ms-1) and upper part (Ms-2), respectively.

The Lagongtang Formation is in fault contact with the Mugagangri Group to the north (Fig. 1c, 3f). The Lagongtang Formation from Ms-3 section near Dongrema town (Fig. 1f, 3f, 3g) and Ms-4 section near the Selazeren town (Fig. 1f, 1d) are of similar composition and are interpreted as turbidites (Fig. 1c, 1d, 1f), consisting of ness rhythmic interbedded medium-fine sandstone, siltstone, and dark mudstone with some lenticular coarse sand beds (Fig. 7). Sandstone beds, commonly arranged in thinning-upward cycles (Fig. 3g), are laterally continuous and mostly vary from 5 to 50 cm thick, and occasionally have erosional bases and fine upward (Fig. 3g). Flute casts were found on the baseside of sandstone layer (Fig. 3f). Lenticular sandstone, with convex-down geometries, extends ~5 m in laterally and ~ 0.5 m in vertically. The rhythmic interbedded sandstones and dark mudstone, fine upward and flute casts were deposited by low-density gravity flows, while the lenticular sandstones were formed in the channels of a middle-distal submarine fan (Miall, 1997; Zhu and Pan, 1986; BGMRXAR, 2014b). A ~4 m width granite dike intrudes the Lagongtang Formation in the Ms-3 section near Dongrema town (Fig. 3g). The thickness of this formation in Ms-3 and Ms-4 is ~130 m and ~50 m, respectively. In the Ms-2 section near Gayouka town (Fig. 1f), the Lagongtang Formation overlies the Xihu Formation above an angular unconformity (Fig. 3c), indicated by nearly horizontal interbeds of siltstone and marlite overlying the strongly deformed argillaceous siltstone with an inclination of 43° . In the Ms-2, the lower part of Lagongtang Formation mainly consists of dark gray-black thin interbedded fine-siltstone and marlite with plane-parallel-lamination (Fig. 6), a ~30 cm of light-gray volcanic ash layer is exposed about 5 m from the bottom (Fig. 6, 3e). The middle part is composed of medium-thin layered gray-black fine sandstone with grayish white lenticular limestone or vice versa (Fig. 3d). Layered sandstone or limestone is rich in fossils debris such as bivalves, corals and ammonites. Lenticular sandstone or limestone is thick in the middle and pinches out gradually toward both ends, ranging in size from >10 m to ~1 m. The upper part is dominated by interbedded gray medium-fine calcareous sandstone and siltstone, which commonly display parallel-lamination. The thin interbedded fine-siltstone and marlite to fine sandstone with lenticular limestone were deposited in marginal reefs to upper slope (Flügel, 2010), while the interbedded calcareous sandstone and siltstone with parallel-lamination were formed in high-energy shallow marine sedimentary (Flügel, 2010). U-Pb ages of the tuffite layer constrains a 140 Ma age for the Lagongtang Formation (Fig. 8; Table 1; Supplementary Tables S1). Seven (2017TF/22/21/66-70) sandstone samples were collected from the Ms-4 section, two sandstones (2019TFD16/17) and two granitic rocks (2019TFD14/15) were sampled from section Ms-3. Three sandstones (2019TFD47/49/50) and one tuffite (2019TFD48) were collected from the lower part and two sandstones (2019TFD44/45) from the upper part of this formation in section Ms-2.

Duoni Formation is variably juxtaposed again the Lagongtang Formation across fault or unconformable contacts (Li et al., 2017b; BGMRXAR, 2014b). In the Ms-2 section (Fig. 1f), the Duoni Formation mainly consists of light grey fine-siltstone with lenticular sandstone and thin layers of coal (Fig. 3h, 6). The lenticulars are large-scale, consisting of coarse-medium sandstones with a large amount of plant debris. Fossils of bivalves and ferns from this formation suggest an Early-Late Cretaceous age (BGMRXAR, 2014b). Lenticulars with plant debris and the coal layer the were formed in channel and marsh of a delta plain. Sandstone samples 2019TFD42/43 were collected from the base of the Duoni Formation in section Ms-2 (Fig. 6).

4. Methods

Thirty-six total samples were collected from the localities summarized above (Fig. 1, 2; Supplementary Table S1) for analysis at the Key Laboratory of Continental Collision and Plateau Uplift in the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Thin-sections were prepared for all samples and the twelve least-altered and coarsest-grained sandstones were selected for petrographic modal analysis (Supplementary Table S3). Thin-sections from the Lagongtang Formation that contained Cr-spinel grains were selected for Cr-spinel geochemical analysis (Supplementary Table S2).

Detrital zircon geochronology followed the approach of Ding et al (2013) and Li et al (2017a), utilizing an Agilent 7500a Quadruple ICP-MS attached to a New Wave UP 193 nm ArF excimer laser-ablation system. The ages reported in the text are 206 Pb/ 238 U ages for grains < 1000 Ma and 207 Pb/ 206 Pb ages for grains >1000 Ma. For petrographic analysis, at least 300 points were counted per slide and crystals larger than 62.5 μm within lithic fragments were counted as mono-crystalline grains following the Gazzi-Dickinson method (Ingersoll et al., 1984). Compositions of spinels were determined using a JXA-8230 Electron Microprobe Analyzer (EMPA). The accelerating voltage was 15 kV, the sample current was 20 nA, and the beam diameter was 5 μm.

5. Results

5.1 Sandstone petrography

Six sandstones from the Quehala Group are moderate to well sorted with mostly subrounded monocrystalline quartz grains (85.6-93.5 %) with less polycrystalline quartz grains (0.9-8.0 %) and feldspars (1.4-5.5 %). Sedimentary lithic fragments (~1.5 %) include sandstone and shale. These samples plot in craton interior provenance field (Fig. 9a, 9d, 9e).

Two sandstone samples from the Xihu Formation are moderate with mostly subrounded-rounded monocrystalline quartz grains (82.4-87.5 %), with feldspars (6.3-9.8 %), and less polycrystalline quartz grains (0.9-1.8 %). These samples plot close to the craton interior provenance field (Fig. 9b, 9d, 9e).

Four sandstone samples from the Lagongtang Formation are dominated by quartz grains (62.7-71.7 %) and lithic fragments (20.2-32.1 %), mostly poorly sorted and angular to subangular in shape (Fig. 9c). Quartz grains are mainly monocrystalline (42.7-55.5 %) and show undulating extinction. Lithic fragments contain sedimentary lithic and volcanic lithic fragments. While, feldspar (4.2-8.4 %) is a minor phase and shows twinning. These samples plot within the recycled orogen provenance field (Fig. 9c, 9d, 9e).

5.2. Cr-spinel compositions

Because of the stability of the physical and chemical properties of spinel, it is a proxy to identify tectonic setting in clastic rocks (Lenaz et al., 2000; Kamenetsky et al., 200l). Chromium-spinel compositions of sample from Lagongtang Formation are characterized by low TiO_2 (generally < 0.1 %) and the Cr# numbers are in the range of 51-89, respectively (Fig. 9f, 9g).

5.3 U-Pb geochronology

5.3.1 Igneous rock zircon U-Pb geochronology

The two granitic vein samples (2019TFD14, 2019TFD15) intruding the Lagongtang Formation near Dongrema town (Ms-3; Fig. 1d, 3f) yielded 37 concordant ages from samples 2019TFD14 and 2019TFD15, producing weighted mean ages of 114.3±1.1 Ma and 113.7±0.7 Ma, respectively (Fig. 8; Supplementary Tables S1). The granitic veins intruded after the sediment, thus constricting the upper limit of the formation age for the Lagongtang Formation.

Sample 2019TFD48 from the tuffite layer in the basal Lagongtang Formation near Gayouka town (Ms-2; Fig.3e) yielded 17 concordant ages between 141-138 Ma, producing a weighted mean age of 139.4±0.6 Ma (Fig. 8). This age constrains the timing of deposition of the Lagongtang Formation to 140 Ma.

5.3.2 Detrital zircon U-Pb geochronology

Zircon crystals extracted from the Quehala Group near Shagong town (Ms-1, Fig. 1e) are mainly subhedral and yield U/Th ratios ranging from 0.37 to 21.27, consistent with typical compositions of igneous zircon. 880 analyses yielded 729 usable ages after application of concordance filters (Fig. 5; Supplementary Tables S1). Major age populations were identified in the ranges of 1200-900 Ma. Additional ages scattered between 900-600 Ma and 1800-1500 Ma.

Zircon crystals extracted from the lower part of Xihu Formation near Shagong town (Ms-1, Fig. 1e) are rounded with U/Th ratios ranging from 0.56 to 14.92, also consistent with igneous zircon. 220 analyses yield 160 ages (Fig. 5; Supplementary Tables S1). Most of the ages cluster between 1200-900 Ma. Additional ages are scattered between 900-700 Ma and 1700-1600 Ma. Age distribution of the upper part of the Xihu Formation from section Ms-2 near Gayouka town are distinct from the lower part. In samples from the upper part, 440 analyses yielded 340 usable ages and the zircon crystals are euhedral to subhedral with U/Th ratios ranging from 0.53 to 13.03. The U-Pb ages are characterized by age-probability peaks at ~146 Ma and ~195 Ma, with minor components scattered between 600-400 Ma.

The crystal characteristics and age distribution of detritus zircon in all samples of Lagongtang Formation are similar. Zircon crystals are mainly euhedral to subhedral with U/Th ratios ranging from 0.1 to 19.08. 1540 zircon grains were analyzed from the Lagongtang Formation, of which 1268 passed the concordance filters (Fig. 6, 7; Supplementary Tables S1). Major age populations lie in the ranges of 300-210 Ma, 1900-1700 Ma and 145-128 Ma with peaks at ~250 Ma, ~1800 Ma and ~140 Ma. Subordinate populations are between 180-160 Ma, 500-400 Ma and 210-185 Ma.

Zircon crystals collected from the Duoni Formation near Gayouka town (Ms-2, Fig. 1f) are rounded-subrounded with U/Th ratios ranging from 0.58 to 9.92. 220 analyses yield 158 usable ages (Fig. 6; Supplementary Tables S1). Samples of the Duoni Formation show the similar age spectrum with the Lagongtang Formation. The most significant age populations are between 300-210 Ma, 200-180 Ma and 140-120 Ma. Additional ages are scattered between 500-400 Ma.

6. Discussion

6.1 Provenance analyses

6.1.1. Potential sources

The Mesozoic strata were deposited within or near the BNSZ, so the most proximal potential sedimentary sources include the Lhasa terrane and the Qiangtang terrane, or a mixed provenance when the BNO was nearly closed. The Songpan-Ganzi terrane and the Qiangtang terrane had already sutured following closure of the Paleo-Tethys Ocean in Early Jurassic time (Ding et al., 2013), while most of the post-orogenic exhumation in the Songpan-Ganzi terrane did not occur prior to 30 Ma (Roger et al., 2010). Therefore, the Songpan-Ganzi terrane can be excluded as a possible source as it was not exposed. Those terranes south of Lhasa could also be ruled out as possible sources because the Neo-Tethys Ocean separating the Lhasa terrane from the Greater India/northern Australia was not closed until Late Cretaceous time (Ding et al., 2005). In order to distinguish the sources of Mesozoic strata in our study area, we compare the age spectra of these formations with published U-Pb age data of detrital and magmatic zircon from the Lhasa and Qiangtang terrane (Fig. 10).

The Permian-Triassic Angjie and Duoburi Formation from the south of Selincuo in northern Lhasa terrane contains 1200-950 Ma, 600-500 Ma and 1700-1500 Ma age populations, and with peaks at ~990 Ma, ~1100 Ma and ~550 Ma (Fan et al., 2017). Age populations of 1150-900 Ma and 600-500 Ma, with peaks at ~ 1100 Ma and ~ 550 Ma (Gehrels et al., 2011) dominate the Permian strata from the south of Amdo in northern Lhasa terrane. The Early Jurassic (210-185 Ma) igneous rocks are widely distributed in the central and southern Lhasa terrane with a dominant age-probability peak at ~195 Ma (Chu et al., 2006; Zhang et al., 2007a, 2007b; Yang et al., 2008; Ji et al., 2009; Zhu et al., 2008, 2011a, 2013). Late Jurassic to Early Cretaceous igneous rocks in the northern and central Lhasa terrane are characterized by 154-129 Ma high relative probability (Volkmer et al., 2007; Jiang et al., 2010; Du et al., 2011; Zhu et al., 2009, 2011b; Chao et al., 2016).

The Triassic sandstones from the Nima area in southern Qiangtang terrane are characterized by 300-210 Ma and 2000-1800 Ma ages (Gehrels et al., 2011). Similarly, the Triassic Riganpeicuo Formation, near the Rongma town in southern Qiangtang terrane, contains major age clusters of 300-210 Ma, 470-400 Ma, and 1950-1800 Ma (Hou et al., 2018). Age distribution of the Jurassic Bilucuo and Shamuluo formations sandstone, which got from Duoma area, contains major age groups between 300-200 Ma, 470-400 Ma, 1950-1800 Ma and 180-160 Ma (Ma et al., 2017, 2018a). Two intense magmatism peaks of ~162 Ma and ~118 Ma were discovered in the southern Qiangtang terrane, and there is a magmatic gap between 140-130 Ma (Guynn et al., 2006; Li et al., 2014; Zhang et al., 2017; Li et al., 2017; Liu et al., 2018; Li et al., 2018).

6.1.2. Provenance of the Quehala Group and Xihu Formation in passive continental margin of northern Lhasa terrane

Sandstone compositions of samples in the Quehala Formation are monocrystalline quartz-rich and lithic-poor showing signatures of the continental terrane provenance (Fig. 9d, 9e). Detrital zircons from these samples are dominated by 1200-900 Ma ages, similar to the Permian-Triassic strata, however the 600-500 Ma age cluster is absent (Fig. 10). The age spectrum is very similar with the Triassic strata from the northeast Indian continent which is also characterized by age cluster 1200-900 Ma (Veevers and Saeed, 2009), which possibly implies that the Lhasa terrane was close to India (Cai et al., 2016) at this time.

Sandstone compositions of samples in the Xihu Formation are monocrystalline quartz-rich and lithic-poor showing signatures of the continental terrane provenance (Fig. 9d, 9e). Combined with the geochemical characteristics of sandstone (Zhou and Zhang, 2009), a passive continental margin setting for the Xihu Formation is likely. In the lower part of the Xihu Formation, major age cluster of 1200-900 Ma is significantly resembling the age pattern of the Triassic Quehala Group (Fig. 10) and thus indicating its provenance of Lhasa terrane.

The detrital zircon age pattern of upper part of the Xihu Formation is different from that of the lower part. It is lacking of age group of around 1200-900 Ma; however, it has two distinct age peaks at ~195 Ma and ~146 Ma respectively. This suggests that the former most likely derived from the Early Jurassic igneous rocks in the southern or/and center Lhasa terrane, as the later came from the Late Jurassic to Early Cretaceous magmatic rocks in the center or/and northern (Chu et al., 2006; Zhang et al., 2007a, b; Yang et al., 2008; Ji et al., 2009; Zhu et al., 2008, 2009, 2011a, 2011b 2013). It is also worth noting that the absence of age clusters of 300-200 Ma and 1950-1750 Ma indicate that the southern Qiangtang terrane is an unlikely source for the upper part of the Xihu Formation. Besides, geological evidence of northward paleocurrent direction also corroborates the provenance of Lhasa terrane for the upper part of the Xihu Formation (Qin et al., 1999; Zhang et al., 2012).

In summary, considering the combined sandstone compositions and their sedimentology, it is clearly that the Quehala Group and Xihu Formation were deposited on the passive continental margin of the northern Lhasa terrane, comprised of sediments from the Lhasa to the south, which are also candidates for the basement of the peripheral foreland basin along the BNSZ.

6.1.3. Provenance of the Lagongtang and Duoni formations in the peripheral foreland basin

Sandstone compositions of samples from the Lagongtang Formation are dominated by quartz grains and lithic fragments plotting within the recycled orogen provenance field (Fig. 9d, 9e). Compared with the Xihu Formation, samples from the Lagongtang Formation show quite different detrital zircon age patterns, characterized by conspicuous 300-210 Ma and 1950-1750 Ma clusters (Fig. 10). The major age groups in the range of 300-210 Ma, 1950-1750 Ma, and minor group of 180-160 Ma are matched well with the Triassic-Jurassic strata of southern Qiangtang terrane (Fig. 10). The cluster of 180-160 Ma may also represent the Middle Jurassic magmatism in southern Qiangtang terrane (Liu et al., 2018). Meanwhile, the minor age clusters of 145-128 Ma and 210-185 Ma may represent the magmatism of Lhasa terrane. The southward and northward bidirectional paleocurrent also indicates the existence of a mixed source for the Lagongtang Formation (Qin et al., 1999; Zhang et al., 2012).

In addition, we also performed analysis of Cr-spinel compositions on samples from the Lagongtang Formation (see the section of “5.2 Cr-spinel compositions”). As stated earlier, the Lagongtang Formation is characterized by low content of TiO_2 (generally <0.1%) and the #Cr numbers are in the range of 51-89, which are inferred most likely to derive from peridotites (Lenaz et al., 2000). In the plot of TiO_2 vs. Al_2O_3, all fall in supra-subduction zone area (Fig. 9f). In the plot of Cr# vs Mg#, according to the classifications of Dick and Bullen (1984), spinels correspond best with Type III peridotites (Fig. 9g), and consistent with the compositions of spinel in the Dingqing ophiolitic rock (Fig. 9g). In other words, sediments of the Lagongtang Formation were likely fed from the BNSZ based on analysis of Cr-spinel compositions. The unconformable contact between the Early Cretaceous Lagongtang Formation and Middle to Late Jurassic Xihu Formation highlights the sedimentary interruption between the two formations (Zhu and Pan 1986; BGMRXAR, 2014a, b; Li et al, 2017c). It is worth mentioning the notable apparent switch of source areas and sedimentary environment between the Xihu Formation and Lagongtang Formation. The Duoni Formation dominated by gray siltstone with thin coal bed. The major age cluster of U-Pb zircon ages between 300-200 Ma suggests derivation from the Triassic-Jurassic strata of the southern Qiangtang terrane. The 140-120 Ma age cluster may come from the magmatism of Lhasa terrane.

In summary, provenance of the Early Cretaceous Lagongtang Formation was from the BNSZ, the southern Qiangtang terrane to the north, and the Lhasa terrane to the south in order of decreasing importance based on our detrital zircon data and Cr-spinel composition data. Similarly, provenance of the Duoni Formation was also from the southern Qiangtang terrane to the north and the Lhasa terrane to the south, again in order of decreasing importance. Deposition atop passive continental margin basement, dominantlynorthern provenance for both units, andsouthward-decreasing thickness of the Lagongtang and Duoni Formations indicates that they were most likely deposited in the foredeep and/or forebulge depozone of a peripheral foreland basin system that formed due to initial Lhasa-Qiangtang collision.

Lagongtang Formation samples are relatively rich in quartz, and poor in lithic grains and feldspar compared to typical sandstone compositions of peripheral foreland basin systems (Fig.9d, 9e; e.g. Najman et al., 2005; DeCelles et al., 2014; Baral et al., 2018). We interpret that this discrepancy arises from the paucity of exposed intrusive igneous rocks in the southern Qiangtang terrane. Furthermore, most of the exposures are concentrated in the west , far from our sample localities (e.g. Pullen et al., 2008; Zhang et al., 2012; Zhai et al., 2013; Li et al., 2014; Liu et al., 2018). Sedimentary rocks of the Lagongtang Formation were mainly recycled from the Jurassic-Triassic strata exposed in the BNSZ and the southern Qiangtang terrane rather than derived from igneous exposures, consistent with the high relative age-probability of300-200 Ma detrital zircon ages. During recycling, quartz is more resistant to weathering, resulting in enrichment of quartz relative to feldspar and lithic grains.

6.2. Implications for the Initial Lhasa-Qiangtang Collision

The Lhasa-Qiangtang collision is considered as the initial contact of continental terranes after disappearance of oceanic lithosphere and the first development of a peripheral foreland basin on the subducting Lhasa terrane (Ding et al., 2017; Li et al., 2017a). This study yields a new maximum depositional age and provenance of the Mesozoic strata provides further information for the initial Lhasa-Qiangtang collision in Dingqing area, along the eastern segment of BNSZ.

The lower part of Xihu Formation is dominantly composed of carbonaceous shale and sandstone with plant debris indicating a delta facies. The similarity of U-Pb age spectrum to the underlying Quehala Formation supports the derivation from the Lhasa terrane source. The upper Xihu Formation with a maximum depositional age ~146 Ma, consists of grayish sandstone, mudstone and limestone, with the parallel bedding and ripple marks, which indicates a shallow sea environment of the passive continental margin of Lhasa terrane (Fig.11a). The detrital zircon age distribution and northward paleocurrent direction also indicate the Lhasa terrane source. A regional unconformity has been reported between the Xihu Formation and the overlying Early Cretaceous (140 Ma) Lagongtang Formation (Zhu and Pan, 1986; BGMRXAR 2014a, b; Li et al, 2017c), which was also clearly observed in the field in this study. This distinct unconformity has long been thought of forming in response to the initial Lhasa-Qiangtang collision and stands for a sedimentary interruption between the two formations (Zhu and Pan, 1986; BGMRXAR 2014a, b; Li et al, 2017c). Based on the age of uppermost Xihu Formation and the age of lowermost Lagongtang Formation, the unconformity we observed in the field spans an age interval of 146-140 Ma. The Lagongtang Formation, is a bathyal-abyssal environment characterized by turbidite near the BNSZ, and is shallow-slope facie deposits of limestone interbedded with mudstone or sandstone about 20 km southward, that two parts may represent the distal foredeep and foredeep depozone, respectively (Fig 11b). The firstly appearance of masses of Permian-Triassic and Paleoproterozoic detritus from the detrital zircon age spectra of Lagongtang Formation indicating the Qiangtang source. This is the first occurrence of the Qiangtang detrital components in the strata of Lhasa terrane, and it indicate that the minimum age of Lhasa-Qiangtang collision was ~140 Ma (Early Cretaceous). Thus, combining with the sharp provenance shift between the Xihu and Lagongtang formations, we propose that the 146-140 Ma regional unconformity between those two formations most likely formed in response to the initial Lhasa-Qiangtang collision occurred at sometime between 146 Ma and 140 Ma at eastern segment of the BNSZ in Dingqing area. The Early-Late Cretaceous Duoni Formation shows fault/unconformity contact with the Lagongtang Formation. Moreover, the Duoni Formation was formed in the delta or marine-terrigenous depositional environments (BGMRXAR, 1993, 2014a, b; Li et al., 2017c) with a mixture source, suggesting that the Duoni Formation may represents the forebulge of the peripheral foreland basin formed by collision between Lhasa and Qiangtang terrane.

The 145-130 Ma magmatic activity gap of the southern Qiangtang indicate collision onset at

~140 Ma that emplaced due to the termination of normal subduction (Zhu et al., 2016). The paleomagnetic data from Shiquanhe area suggests onset of collision at ~151 Ma (Ma et al., 2018b). The latest paleomagnetic analysis from south of Shuanghu county implies that the width of the BNO was 2,600 ± 710 km during the Middle Jurassic (Cao et al., 2019). Our results, in combination with previous work, suggest that initial Lhasa-Qiangtang collision occurred at 146-140 Ma in the eastern part of BNSZ.

6.3 Implications for collision mode of the BNSZ

A scissor-like continental collision model that commenced from east to west for the Lhasa-Qiangtang collision are widely quoted although this tectonic model has not been effectively tested (Fig. 12a; Yin and Harrison, 2000; Pan et al., 2004; Zhu et al., 2013; Yan et al., 2016). However, our data combined with predecessors, this paper is more in favor of the collision of the Lhasa and Qiangtang terranes was synchronous (Fig. 12b; Zhang et al., 2012, 2014; Wang et al., 2016). The evidence is as follows: 1) A mature peripheral foreland basin was identified in the Dingqing area, that provide an accurate 146-140 Ma age for the initial Lhasa-Qiangtang collision in the eastern part of BNSZ (this paper). 2) Southward-directed paleocurrent and the lithic-rich of the Lower Cretaceous sandstone in Duba area (Leier, 2005, 2007) and Asa basin (Zhang et al., 2014) suggest the BNSZ and southern Qiangtang terrane provenance, that indicating the existence of possible foreland basin and narrowing the Lhasa-Qiangtang Collision occurred at the earliest Cretaceous in the middle segment of BNSZ. 3) ~60% north-south shortening of the Lhasa crustal occurred during the Early Cretaceous in Coqin area (Murphy et al, 1997) and major deformation and exhumation occurred at Early Cretaceous in Nima, Gaize and Domar area (Paul et al., 2005, 2007; Raterman et al., 2014), all these events can be attributed to the continuous compression after the initial Lhasa-Qiangtang collision in the earliest Cretaceous. 4) Provenance analysis of the Late Jurassic to Early Cretaceous Wuga Formation in Gaize county, western segment of BNSZ, shows a north provenance from the BNSZ and Qiangtang terrane and a possible foreland basin setting, that suggesting ~150 Ma for the initial Lhasa-Qiangtang collision (Li et al., 2017). In conclusion, the initial collision timing of Lhasa-Qiangtang is simultaneous from the western Gaize to the central Nima and Naqu to the eastern Dingqing, and occurred in the earliest Cretaceous (Fig. 11b, 12b).

7. Conclusions

Field observations, U-Pb isotopic ages of detrital zircons, Cr-spinel analysis and petrographic investigations of the Mesozoic sequence developed along the northernmost margin of the Lhasa and within the BNSZ in and around Dingqing area of central Tibet have led us to draw following concluding remarks:

1. Detritus of the Middle-Late Jurassic (~170-146 Ma) Xihu Formation were derived from the Lhasa terrane in the south and deposited on the passive continental margin on the northern Lhasa terrane.

2. The Lagongtang Formation was formed during Early Cretaceous (140 Ma) and developed in a mature peripheral foreland basin in response to the initial Lhasa-Qiangtang collision with major provenance of the Qiangtang terrane to the north.

3. A ~146-140 Ma angular unconformity between the Xihu Formation and Lagongtang Formation is interpreted to mark the migration of flexural forebulge through this region.

4. The final closure of the BNO as well as the initial contact between the Lhasa and Qiangtang

terranes are most likely to occur at the time interval of 146-140 Ma indicated by abrupt provenance and depositional environment transition which are identified in the Lagongtang Formation.

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