The disappearance of a Late Jurassic remnant sea in the southern Qiangtang Block (Najiangco area): implications for the tectonic uplift of central Tibet

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Abstract

Located between the Bangong-Nujiang suture zone and the Qiangtang Block in central Tibet, the Najiangco area (~5 km to the north of Nima-Selingco) contains an Upper Jurassic-Lower Cretaceous sedimentary succession deposited during a period of marine regression. The youngest marine sedimentary unit in the Najiangco area is the Upper Jurassic Shamuluo Formation, which consists of sandstone, limestone, siltstone, and shale. Sedimentary facies analysis shows that tidal flat and subtidal lagoonal facies characterized the northern margin of the basin, while delta front and prodelta facies dominated the middle part, and carbonate shoal and patch reef facies prevailed along the southern margin. Provenance analysis, including petrographic modal analysis of sandstones and U-Pb dating of detrital zircons, shows that a recycled orogen in the central Qiangtang to the north of Najiangco area was the source of the sandstones in the Shamuluo Formation. Biostratigraphy and U-Pb zircon dating of a porphyritic granitoid dike (150.8 ± 1.9 Ma) indicate that the Shamuluo Formation was deposited during the Late Jurassic (Oxfordian to Kimmeridgian). During Middle Jurassic time, the southern Qiangtang Basin was dominated by shallow-marine environments. Later, during the Late Jurassic (Oxfordian to Kimmeridgian), the shallow-marine facies retreated to the southern margin of the basin. Combined with regional paleogeographic data from central Tibet, two stages of southward retreat of the Qiangtang remnant sea, and three stages of topographic uplift of the Qiangtang Block can be recognized during late Middle Jurassic to Early Cretaceous time.

Keywords: Shamuluo Formation; Stratigraphy; Sedimentology; Provenance; Coral; Foraminifera.

1. Introduction

When and how the Tibetan Plateau reached its current high elevation (~5 km) remains an outstanding question. Many studies have suggested that the Tibetan Plateau primarily grew during the Cenozoic India-Eurasia collision (Hetzel et al., 2011; Rowley and Currie, 2006; Tapponnier et al., 2001). Other studies have suggested that the initial uplift of central Tibet occurred during the Late Jurassic to Cretaceous Lhasa-Qiangtang collision, along the Bangong-Nujiang suture zone (Guynn et al., 2006; Kapp et al., 2007; Murphy et al., 1997; Raterman et al., 2014). The Qiangtang Block, located in the central part of Tibetan Plateau, is a key locality to test the presence or absence of an elevated pre-Cenozoic plateau. It is bounded to the north by the Jinsha suture zone and to the south by the Bangong-Nujiang suture zone (Fig. 1A). In its central part, an east-west-trending mountain ranges divides it into northern and southern parts (Fig. 1A).

The Qiangtang Block achieved an elevation of >5000 m by the middle Oligocene (~28 Ma) based on paleoelevation reconstructions using stable isotopes (Xu et al., 2013). However, this height may have been reached earlier. Thermochronological data show that the Qiangtang Block experienced rapid to moderate cooling and exhumation by circa 45-40 Ma (Rohrmann et al., 2012; C. Wang et al., 2008), and zircon helium dating shows accelerated exhumation (around 0.2–0.3 mm/a) of the southern Qiangtang Block beginning around 150 Ma (Zhao et al., 2017). Based on analysis of sedimentary facies, the Qiangtang Block was uplifted above sea level by Early Cretaceous time, and shed detritus southward into the Bangong-Nujiang suture zone and the northern Lhasa sedimentary basin during the Early Cretaceous (DeCelles et al., 2007; Leier et al., 2007; Sun et al., 2017).

The disappearance of the sea, and onset of continental uplift could in theory be directly constrained by the youngest marine strata and oldest continental red beds. However, the question of whether marine sedimentation in the southern Qiangtang region and Bangong-Nujiang suture zone continued as late as the Early Cretaceous, or instead terminated during the Late Jurassic, remains debated due to conflicting sedimentary, geochemical and biostratigraphic data (Baxter et al., 2009; Girardeau et al., 1984; Kapp et al., 2007; Yin, 2016; Zhang et al., 2002). Besides, the marine environment may even be suggested to prevail into Late Cretaceous time, as some authors report the remnants of oceanic seamounts or oceanic plateaus dating to 132-108 Ma within the Bangong-Nujiang suture zone. (Fan et al., 2014a; Zhang et al., 2014).

The shallow-marine Shamuluo Formation consists of both siliciclastic and carbonate strata, and contains the youngest mappable marine strata exposed in the southern Qiangtang Block and Bangong-Nujiang suture zone (Fig. 1B). Previous studies have mainly focused on the provenance and tectonic implications of the Shamuluo Formation (Huang et al., 2017; Li et al., 2017a). Less attention has been paid to its stratigraphy, sedimentology and paleogeography, and its implications for topographic uplift of the Qiangtang Block. In this paper, we report new stratigraphic and sedimentary, and provenance data of the Shamuluo Formation in the Najiangco area (Figs. 1C and 2). Based on these data, we discuss Late Jurassic paleogeography and tectonics to explain the disappearance of the sea and regional topographic uplift of the southern Qiangtang Block in central Tibet.

2. Geologic background

2.1 Qiangtang Block

The Qiangtang Block, bounded to the north by the Jinsha suture zone and to the south by the Bangong-Nujiang suture zone, can be divided into northern and southern terranes by the central Qiangtang assemblage (Fig. 1A). The northern and southern Qiangtang terranes are characterized Mesozoic shallow-marine to littoral limestones and siliciclastics (Zhang et al., 2002). The central Qiangtang area is characterized by Triassic high-pressure metamorphic mélanges (e.g., Kapp et al., 2000; Pullen and Kapp, 2014) and Paleozoic ophiolites (e.g., Li, 1987; Zhai et al., 2016), as well as Paleozoic sedimentary strata (e.g., Kapp et al., 2000) and Late Triassic granitoids (e.g., Kapp et al., 2003; Kapp et al., 2000; Li et al., 2015; Wu et al., 2016) (Fig. 1B). The Paleozoic strata are slightly metamorphosed and contain detrital zircons, which yield ages mainly between 1100 and 500 Ma, with peaks at ~550 Ma, ~630, ~800 and ~950 Ma; zircons >1.1 Ga show peaks at 1870 and 2500 Ma (Dong et al., 2011; Gehrels et al., 2011; Pullen et al., 2011). It is hotly debated whether there is a suture zone in central Qiangtang area (e.g., Li, 1987; Kapp et al., 2000; Pullen and Kapp, 2014; Wang et al., 2008; Zhang et al., 2016).

Our previous study have established a systematic stratigraphic, sedimentary, and tectonic framework for the Mesozoic southern Qiangtang Basin (Ma et al., 2017). Hereby, we summarize the Upper Triassic to Lower Cretaceous strata in brief in the next paragraph.

Upper Triassic sandstones on the southern Qiangtang Block show affinities with Qiangtang Paleozoic strata, and also yield U-Pb zircon ages recording a Late Triassic igneous event. The Jurassic succession includes Toarcian-Aalenian shallow-marine limestones (the Quse Formation), Aalenian-Bajocian deltaic sandstones (the Sewa Formation) and Bathonian outer platform to shoal limestones (the Buqu Formation) (Fig. 3). The deep-water Gaaco Formation can be correlated with the shallow-marine Sewa Formation (Fig. 3). The Quse, Sewa and Buqu formations are unconformably overlain by upper Bathonian to Callovian fan-delta conglomerates and sandstones (the Biluoco Formation) and Callovian platform limestones (the

Suowa Formation) (Fig. 3). This Jurassic sequence is unconformably overlain by the coarse clastic intermontane deposits of the Upper Cretaceous Abushan Formation (Fig. 3). Facies analysis of the Jurassic strata indicates that during the Early-Middle Jurassic, the southern Qiangtang Basin deepened to the south. The Sewa and Gaaco formations include continental-arc volcanic detritus, indicating a forearc setting (Fig. 3). The Biluoco Formation records a clear change in provenance to more recycled sedimentary sources (Fig. 3), indictating tectonic uplift of an orogenic source to the north, which was further interpreted as a late Bathonian collision between the Qiangtang and another microcontinent, perhaps the Lhasa Block.

The southern Qiangtang Block is cut by three major Cenozoic thrust faults (Fig. 1B) (Kapp et al., 2005). The Zadaona-Riganpei Co thrust system juxtaposes central Qiangtang Paleozoic strata and mélanges in the hanging wall over southern Qiangtang Mesozoic marine strata in the footwall. The Southern Qiangtang thrust juxtaposes the Mesozoic strata of the southern Qiangtang Basin against the Shamuluo Formation (Jr unit in Kapp et al., 2005). The Shiquanhe-Gaize-Amdo thrust system juxtaposes the Shamuluo Formation over Cretaceous-Tertiary nonmarine strata and the Mugagangri Group (Jr_1m unit in Kapp et al., 2005).

The Jurassic to Cretaceous succession in the northern Qiangtang Basin was named the Yanshiping Group, which is divided into the Quemoco, Buqu, Xiali, Suowa, and Xueshan formations (Yao et al., 2011). The Quemoco, Xiali, and Xueshan formations are subaerial to shallow-marine clastic rocks, and are difficult to correlate with strata in the southern Qiangtang Basin (Ma et al., 2017). The Buqu and Suowa formations are shallow-marine limestones deposited during Bathonian and Callovian time, respectively, and are similar to their equivalents in the southern Qiangtang Basin (Ma et al., 2017; Wang et al., 2008; Yin, 2016). However, corals collected from the Suowa Formation in the Bandao Lake area in the northern Qiangtang suggest that marine environments persisted into the Late Jurassic (Sun et al., 2013), or possibly even into the Early Cretaceous as suggested by pollen fossils (Li and Batten, 2004; Sun et al., 2013) and marine oil shale Re-Os dating (Fu et al., 2008).

2.2 Bangong-Nujiang suture zone

The strata in the Bangong-Nujiang suture zone include the Upper Triassic to Lower Jurassic Mugagangri Group, the Upper Jurassic to Lower Cretaceous Shamuluo and Dongqiao formations, and the Lower Cretaceous Qushengla Formation (Institute of Tibetan Geological Survey, 2006a) (Fig. 3). The Mugagangri Group consists of interbedded sandstone and argillite, as well as mélanges with a blocks-in-matrix structure; the blocks are composed of chert, limestone, sandstone, and basalt (Zeng et al., 2016). Based on the petrographic composition and the youngest detrital zircons, the Mugagangri Group can be divided into three subunits, namely the Triassic Tma, Triassic to Jurassic TJmb, and Jurassic Jmc (Li et al., 2017a; Zeng et al., 2016). The Mugagangri Group was originally deposited in a submarine fan environment, then incorporated into a subduction complex related to the northward subduction of the Bangong-Nujiang oceanic lithosphere (Huang et al., 2017; Li et al., 2017a; Zeng et al., 2016). Some authors interpreted intraplate-type basalts in the suture zone as seamounts (Fan et al., 2014a; Fan et al., 2014b; Zhu et al., 2006) or oceanic plateaus (Zhang et al., 2014) of Jurassic to Early Cretaceous age. Early Cretaceous seamount or oceanic plateau was alternatively interpreted as post-collisional basalt due to slab break-off (Li et al., 2017b; Zhu et al., 2016).

First established in the year 1987 in Alongco (Fig. 1B), the Shamuluo Formation was defined as a unit of unmetamorphosed, fossiliferous siliciclastic sandstones, argillites, and limestones deposited in shallow-marine environments during the Late Jurassic (Fan et al., 1987). It is exposed between Mesozoic strata in southern Qiangtang and the Bangong-Nujiang suture zone mélange (Fig. 3), and is in unconformable contact with the underlying Mugagangri Group (Deng et al., 2017; Li et al., 2017a; Xie et al., 2010). The Shamuluo Formation was deposited during the Late Jurassic, based on identification of coral, stromatoporoid, chaetetid, and brachiopod species (Table S1) (Fan et al., 1987; Institute of Tibetan Geological Survey, 2006a; Ji et al., 2011; Liao et al., 2012). Some authors have suggested that Shamuluo deposition may have persisted into Early Cretaceous time, based on certain coral species (Chen et al., 2004), large benthic foraminifera (Liao et al., 2006; Xie et al., 2010), and a few detrital zircon grains (Huang et al., 2017; Li et al., 2017a). Provenance analysis shows that the Shamuluo Formation was sourced from Qiangtang terrane to its north (Huang et al., 2017; Li et al., 2017a). Based on unconformable relationship with the underlying accretionary complex (the Mugagangri Group), shallow marine environment, and Qiangtang provenance, the Shamuluo Formation was interpreted to have been deposited in a trench-slope basin prior to the Lhasa-Qiangtang collision (Li et al., 2017a), or in a residual-sea basin during the syn-collisional stage (Huang et al., 2017; Li et al., 2017a).

The Dongqiao Formation (also called the Zigetang Formation) directly overlies ophiolites in the Dongqiao and Amdo areas (Fig. 1C). It includes conglomerate grading into sandstone and limestone, indicating transgression up-section (Girardeau et al., 1984). Girardeau et al. (1984) reported corals, algae, foraminifers, and dasycladacae from the Dongqiao Formation, broadly suggesting a Late Jurassic – Early Cretaceous age. The Lower Cretaceous (110-100 Ma) Qushenla Formation, containing extrusive continental volcanic rocks, is exposed along the Bangong-Nujiang suture zone, interbedded with clastic red beds (Chen et al., 2015; Institute of Tibetan Geological Survey, 2006a) (Fig. 3).

2.3 Lhasa Block

The Lhasa Block is located to the south of the Bangong-Nujiang suture zone and to the north of the Yarlung-Zangbo suture zone (Fig. 1A). It can be subdivided into northern, central, and southern terranes, distinguished by different magmatic and sedimentary units (Zhu et al., 2011). The southern Lhasa terrane consists of the Late Triassic to early Cenozoic Gangdese magmatic arc (Chu et al., 2006; Ji et al., 2009; Zhu et al., 2011) and Xigaze forearc basin (Göpel et al., 1984; Schärer et al., 1984; Cai et al., 2012; An et al., 2014; Orme and Laskowski, 2016). The central Lhasa terrane contains widespread Permo-Carboniferous and Jurassic sedimentary strata (Leeder et al., 1988; Yin et al., 1988), with sparser Triassic deposits (Li et al., 2014). It also contains Lower Cretaceous volcanogenic strata (e.g., the Zenong Group) and Mesozoic plutonic rocks dated to between 215 and 95 Ma (Zhu et al., 2011). The northern Lhasa terrane is dominated by a thick Cretaceous sedimentary succession (Leeder et al., 1988), with Jurassic mainly deep-marine turbidite named as Jienu Group (Institute of Tibetan Geological Survey, 2002). The Lower Cretaceous is dominated by shallow-marine deposits (the Duoni and Langshan formations), grading into continental red beds (the Jingzhushan Formation) by the Late Cretaceous (Leier et al., 2007; Sun et al., 2017). Detrital zircons from pre-Jurassic strata in the Lhasa Block are characterized by an age peak of 1250-1050 Ma with subordinate peaks at 1650-1450 Ma and 1900-1700 Ma (Li et al., 2014; Wang et al., 2016). This pattern is different from the Qiangtang Block, which shows peaks at 1050-750 Ma, 1850 Ma, and 2500 Ma (Dong et al., 2011; Gehrels et al., 2011; Pullen et al., 2011). Among < 1 Ga zircons, 560 Ma and 300 Ma are the two most prominent age populations on the Lhasa Block, with subordinate age peaks at 490, 370, 340 and 230 Ma (Li et al., 2014; Wang et al., 2016); this also differs from the Qiangtang, which shows peaks at 300-200 Ma and 500-400 Ma.

3. Sampling and methods

3.1 Stratigraphy and sedimentology

Four stratigraphic sections of the Shamuluo Formation (the Xiede, Najiangco, Gaaco and Jiarebuco sections; Fig. 2) were measured and described in the field. In addition, detailed sedimentological work was conducted on four other localities (the Zumu, Tukari, Aobao, and Kangqiong localities) in the Najiangco area (Fig. 2). GPS coordinates are given in Fig. 4.

Sedimentological features of clastic rocks, including texture, structure, composition, and lithology, were described in order to interpret their depositional environments. Microfacies analysis was carried out on limestones of the Shamuluo Formation in the Gaaco section, at Tukari and Zumu localities, and in the upper part of the Xiede section. The limestones were described in detail from bottom to top in the field. Ninety-five samples were collected with a sample frequency of approximately 1 m for the Gaaco section. Thirty-two samples (including clastic rocks) were collected in the upper part of the Xiede section, as well as ten from Tukari locality and eight from the Zumu locality. Classification of limestone was based on Dunham (1962), as integrated by Embry and Klovan (1971); microfacies definition and interpretation are after Flügel (2010). In this study, the terminology "mudstone" is one type of limestone as Dunham (1962) defined, and does not refer to siliciclastic rocks. Twenty-two coral samples were collected for identification to constrain the depositional age. Of these, eight were from the Xiede section (Samples 16XD12 to 16XD55), nine from Tukari locality (Samples 15SL28 to 16XL39), and five from Aobao locality (Samples 16NJ57 to 16NJ63). Twenty-four limestone samples from the Gaaco section were selected for benthic foraminifera-based biostratigraphic study under thin-section. Age interpretation is based on first appearance shallow benthic zones and letter stages after BouDagher-Fadel (2018a) relative to the planktonic biostratigraphical time scale of BouDagher-Fadel (2018b, as calibrated against the biostratigraphical time scale and the radioisotopes (as defined by Gradstein *et al.*, 2012 and revised by Cohen *et al.*, 2017).

3.2 Sandstone petrography

Twenty-four sandstones, exhibiting minor diagenetic alteration, were selected for petrographic modal analysis, including 14 samples from the Najiangco section and 10 samples from the Xiede section. Approximately 400 grains were identified and counted in each sample, following the Gazzi-Dickinson method (Dickinson, 1985; Gazzi, 1966); crystals or grains larger than 62.5 μm in diameter within rock fragments were counted as single minerals (Ingersoll et al., 1984). The results are presented in Supplementary Table S2.

3.3 Zircon U-Pb dating

Four sandstone and two igneous rock samples were crushed and processed for heavy-minerals via elutriation and magnetic separation. Zircon grains were hand-picked, mounted in epoxy resin, and polished. Cathodoluminescence (CL) images of zircons from the two porphyritic granitoid samples were obtained prior to U-Pb dating, in order to characterize their internal structure and choose potential target sites. U-Pb dating of zircons was conducted using an ICP-MS (Agilent 7500a) equipped to a GeoLas Pro 193 nm laser sampler at the State Key Laboratory of Mineral Deposits Research, Nanjing University, following the methods described by Jackson et al. (2004). A laser beam diameter of 32 μm was used. Zircon standard GEMOC GJ-1 with 207Pb/206Pb age of 608.5 ± 1.5 Ma (Jackson et al., 2004) was used for calibrating the U–Pb fractionation and zircon standard Mud Tank with an age of 732 ± 5 Ma (Black and Gulson, 1978) for accuracy monitoring. Software GLITTER (version 4.4) was used to calculate raw data ((www.mq.edu.au/GEMOC; Griffin et al., 2008). Isoplot 4 software (Ludwig, 2011) was used for plotting probability density curve and calculating weighted mean age. $^{206}Pb/^{238}U$ zircon ages were chosen for grains <1000 Ma and $^{207}Pb/^{206}Pb$ ages for grains >1000 Ma. Zircons older than 200 Ma with discordance <10%, and those younger than 200 Ma with discordance <20%, were presented. The complete dataset is reported in Supplementary Table S3.

4. Results

4.1 Sedimentology and Stratigraphy

4.1.1 Xiede section

The Shamuluo Formation in the Xiede section can be divided into two intervals (Fig. 4A and 5). The 250 m-thick lower interval is mainly composed of limestone, fine- to very fine-grained sandstone, and argillite (Fig. 5). Mudstones containing siliciclastics and bioclasts appear at the base of the section, and grade upwards into limestones with no siliciclastics, increasingly interbedded with very fine-grained sandstones (Fig. 5). Thin-bedded fine- to very fine-grained sandstones, interbedded with limestone or argillite, predominate throughout the remainder of the section (Fig. 5). In some horizons, the sandstone contains elongated argillite intraclasts and flaser beddings (Figs. 4B and 6A); the limestone contains marine fossils such as bivalves, gastropods, and sparse enchinoderms. Sporadic coral-bearing limestone beds generally contain siliciclastic detritus (Fig. 6B). Fine-scale cyclical interbedding of sandstone and argillite is observed (Fig. 4C), and bioturbation is visible in some very fine-grained sandstones (Fig. 6C) and muddy micrite. Normally-graded shell beds with erosional bases occur throughout the section.

We interpret the Shamuluo Formation in the lower part of the Xiede section to have been deposited in a mixed siliciclastic-carbonate environment, probably a tidal flat or shallow subtidal zone. The fine to very fine sandstones, which locally contain argillite intraclasts or are interbedded with siltstone or argillite, are interpreted to have been deposited in a tidal sand-mud flat, with every periodic sandstone-argillite couplet representing one complete tidal period (Archer and Johnson, 1997). The limestones, which contain terrigenous siliciclastic materials, bioclasts, and argillite clasts, are interpreted to have been deposited in a subtidal low-energy zone, with coral biostromes dominating locally (see similar example in Morelock et al., 1983; Tudhope and Scoffin, 1994). Normally-graded shell beds with erosional bases may have been deposited during storms.

The Shamuluo Formation in the upper part of Xiede section is ~46 m-thick and mainly composed of argillite, limestone, and transitional lithology (Figs. 7 and 8). Five microfacies

(Fig. 7) are recognized: MF1-fine to very fine sandstone: Some showing couplets of sandstone and argillite in thin section (Fig. 7A). MF2-oolitic grainstone: Detrital fragments occur dispersed throughout the sparite matrix, or serve as nuclei for ooids (Fig. 7B). MF3-muddy siltstone, shale, or bioclast-bearing mudstone: Bioturbated in many places (Fig. 7C). MF4-floatstone or rudstone: showing a sharp contact with MF3. The bioclasts contained include corals, enchinoderms, gastropods, and bivalves and are sometimes preferentially aligned. Limestone intraclasts and terrigenous siliciclastic detritus also occur (Fig. 7D). MF5-coral framestone (Fig. 4D): The framestones are characterized by thickets of ramose corals forming an open framework, implying that the corals were in place and performed a structural, reef-building function.

We interpret the MF1 microfacies to indicate a tidal flat environment. MF2 may have been deposited in a range of environments, but here we tentatively interpret it as storm deposits in a subtidal zone. MF3 was deposited in a subtidal environment, with both terrigenous components and a marine carbonate factory contribution. MF4 represents storm deposits. MF5 represents biostromes that accumulated in a subtidal environment.

The Shamuluo Formation in the upper part of Xiede section is interpreted to have been deposited in tidal flat to subtidal environments. Subtidal environments, as indicated by the presence of argillite and mudstone containing siliciclastic materials (MF3), are predominant throughout the section. Near the base of the measured section, subtidal environments (MF3) alternate with oolitic grainstones (MF2) that likely represent storm deposits. Tidal flat environments become more prevalent up-section, as reflected in fine-grained sandstones, rhythmically interbedded with argillite (MF1) (Fig. 7A). The environment ultimately transitioned back to subtidal facies (MF3), which were frequently influenced by storms, as recorded in bioclastic floatstone or rudstone beds (MF4). Biostromes, preserved as coral framestones (MF5), developed as coral thickets in the subtidal zone.

Coral fossils collected from the Xiede section (both the lower and upper intervals) include *Cladophyllia minor* Beauvais, *Thecosmilia minuta* Koby, ?*Thecosmilia* sp., *Cladophyllia* sp., *Thecosmilia dichotoma* Koby and *Thecosmilia* cf. *dichotoma* Koby (Figs. 6G and S1), indicating a Late Jurassic (probably Oxfordian-Kimmeridgian) depositional age for the Shamuluo Formation.

4.1.2 Najiangco section

The Shamuluo Formation in the Najiangco section is ~400 m thick (Figs. 4E and 9). The predominant lithology is thinly-bedded, fine-grained sandstone interbedded with siltstone/shale or limestone (Fig. 4F), with a variable sandstone/argillite ratio. Some argillites are bioturbated (Fig. 6D), while others are ripple laminated. Sedimentary structures are sparse in the intercalated fine-grained sandstones, with only rare ripple lamination. Medium-bedded sandstones occasionally show parallel lamination. Most sandstone beds are tabular and laterally continuous, but some show pinch-and-swell shapes. Sporadic shell beds, and oolitic or bioclastic grainstones with a mixed micrite and argillaceous matrix, show sharp basal contacts, and appear as resistant ledges in the section (Fig. 9). Bioclasts include bivalves, brachiopods, crinoids, echinoid spines, and gastropods; ooids show thin or thick cortices, coating bioclastic or siliciclastic nuclei.

We interpret the Shamuluo Formation in the Najiangco section to be a mixed siliciclastic-carbonate system, likely deposited on a marine shelf in a delta front setting. The mudstone and argillite are interpreted to have settled from suspension in a submarine inter-distributary bay, and a mouth bar front where bioturbation is heavy (Fig. 6D), or a low-energy prodelta. The fine to very fine sandstones and siltstones may have been deposited as levees or submarine mouth bars. The lenticular fine to medium sandstones likely reflect fluvial action in distributary channels. The environment was prone to storms, as suggested by the shell beds and oolitic grainstones, with their varied complements of bioclasts and siliciclastic detritus.

4.1.3 Gaaco section

The Shamuluo Formation in the Gaaco section is ~130 m thick and composed of limestone with no siliciclastic contribution (Fig.10). Four microfacies types (Figs. 7E and F) are recognized in the limestones of the Gaaco section (Fig. 4G): MF6-oncoid rudstone and floatstone: Oncoids are 2-4 centimeters in diameter, and have bioclast or ooid nuclei with concentric encrusting laminations. Ooids also occur in this microfacies. MF7-oolitic grainstone: Dominated by concentric ooids, with some bioclasts, limestone fragments, peloids, and aggregates. In well-sorted samples, beds of different ooid size can be observed in thin section. Benthic foraminifera occur as nuclei of ooids or isolated clasts, along with scattered coral fragments. MF8-bioclastic mudstone, wackestone, packstone and floatstone: This microfacies contains bioclasts showing high diversity, including bivalves, brachiopods, gastropods, algae, and crinoids. MF9-bivalve framestone: *In situ* bivalve shells thicker than 2 mm, clustered together to form a rigid framework, with micritic matrix.

We interpret microfacies MF6 and MF7 to indicate a shoal environment, with MF6 more proximal to shoreline. MF8 indicates an outer platform setting. MF9 represents a biostrome in an outer platform.

The Shamuluo Formation in the Gaaco section is dominated by shoal facies in the lower part of the section, as indicated by oncoid rudstone and floatstone (MF6) and oolitic grainstone (MF7), grading up-section into outer platform facies, as evidenced by bioclastic mudstone, wackestone, packstone and floatstone (MF8), with occasional shoals and bivalve biostromes (MF9) (Fig. 10). Coral patch reefs occur along strike in Shamuluo Formation limestones about 2 kilometers east of the Gaaco section.

Twenty-four limestone samples (highlighted in the sample list in Fig. 10) from the Gaaco section were selected for benthic foraminifera-based biostratigraphic study. *Cladocoropsis mirabilis* Felix (Fig. 11K), which indicates Oxfordian – Kimmeridgian age, occurs in samples 15GA16, 26, 27 and 55. The Kimmeridgian assemblage *Everticyclammina virguliana* (Koechlin) (Fig. 11G, H), *Siphovalvulina* sp. (Fig. 11A), *Andersenolina elongata* (Leupold) (Fig. 11J), *Involutina* sp. (Fig. 11C), *Pseudocyclammina lituus* (Yokoyama) (Fig. 11B), *Rectocyclammina chouberti* Hottinger (Fig. 11I), *Lituosepta* sp. (Fig. 11F), and *Mesoendothyra izumiana* Dain (Fig. 11D, E) occurs up-section (samples 15GA42-95). These foraminifera data show that the Gaaco section limestones were deposited during Kimmeridgian, with its lower part maybe as early as Oxfordian.

4.1.4 Jiarebuco section

The Shamuluo Formation in the Jiarebuco section is dominated by shale and siltstone, interbedded with fine- to very fine-grained sandstone (Fig. 4J). A 23 m-thick section was measured across a hillside (Fig. S3). The sedimentary layers are generally tabular, with some lenticular sandstone layers. Unbroken brachiopod shells occur in the sandstone, and pleopod trace fossils were found in shales. Below the measured section, mudstone containing sparse bivalve and crinoid bioclasts is interbedded with shale. Its contact with the measured section is ambiguous because of poor outcrop exposure in a small gully.

The fossils in the Jiarebuco section may imply a marine environment. The assembly of shale and sandstone is quite similar to that of the Najiangco section, which was deposited in a delta front to prodelta setting. However, the Jiarebuco section contains more argillite, suggesting a lower energy environment further removed from submarine channels and sand bars.

4.1.5 Other localities

The Zumu locality is located 50 km west of the Gaaco section, adjacent to the southernmost margin of the outcropping Shamuluo Formation (Figs. 2 and 4H). The Zumu section at Zumu locality was not measured but its Google image can been seen in Fig. S4.

Based on field observations and lithofacies identifications in the thin sections in the lab, the limestones in the Zumu section consist of >400 m monotonously interbedded oncoid rudstone (MF6) (Fig. 4I) and oolitic grainstone (MF7). Both microfacies indicate a very shallow and high-energy shoal environment.

Patch reef assemblages occur in the Tukari locality (Fig. 4J). This assemblage can be subdivided into two units. The massive limestone to the south shows a clast-supported, brecciated texture. The individual limestone blocks include coral limestone, which may be sourced from coral reefs. This unit is interpreted to represent the reef front. It grades gradually to the north into a massive framestone constructed by coral thickets, which represents the *in situ* reef crest. Coral fossils in Tukari locality include *Thecosmilia* ? sp., *Cladophyllia dichotoma* (Goldfuss), *Cladophyllia* cf. *excelsa* (Koby), *Cladophyllia conybearei* Milne-Edw. & Haime, *Stylina* ? sp., *Stylina bangoiensis* Liao & Xia and *Thecactinastraea krimensis* Turňsek (Figs. 6H and S1), suggesting a Late Jurassic (most probably Oxfordian-Kimmeridgian) age.

At Aobao locality, the Shamuluo Formation is dominated by limestone and argillite. We observed both coral and bivalve biostromes (Fig. 4L). Like Najiangco section, this site was influenced by fluvial sediment input, but as it was located further away from the submarine channel, it contains much more argillite. The coral fossils include *Thecosmilia minuta* Koby, *Thecosmilia dichotoma* Koby, *Thecosmilia trichotoma* (Goldfuss) and *Fungiastraea arachnoides* (Parkinson) (Figs. 6I and S2), also indicating Late Jurassic (likely Oxfordian-Kimmeridgian) age.

In Kangmen locality (32°04′46.31"N, 87°59′45.45"E), the Shamuluo Formation is characterized by frequent interbedding of very fine sandstone and argillite, intercalated with limestone. All of the sandstone, argillite, and limestone layers are thinly bedded. Some of the limestone beds are bioclastic rudstones. The Shamuluo Formation in Kangmen was deposited mainly in a delta front environment, with the rudstones representing storm deposits.

4.1.6 Stratigraphic relationships

Three kilometers to the west of Gaaco section, the Shamuluo Formation is in fault contact with basalts, which might represent ophiolite fragments (Fig. S5A). The basalts are exposed along an east-west striking lineament, with Shamuluo Formation limestones dipping to the north exposed to both the north and south (Fig. S5A).

The Shamuluo Formation is mainly exposed to the north of the Mugagangri Group, with the contact striking east-west. The Shamuluo limestone always dips to the north (Figs. S5B, C and D). Some authors have suggested that the Shamuluo Formation unconformably overlies the Mugagangri Group (Deng et al., 2017; Li et al., 2017a; Xie et al., 2010). However, tectonic breccia occurs along the contact (Figs. S5E and F), implying a fault. The breccia consists mainly of Shamuluo Formation limestones, which are pervasively dissected and deformed by small-scale joints and carbonate veins. Further south, Shamuluo Formation limestones with corals can be found scattered in the suture zone, above the buried contact with the Mugagangri Group (Figs. S5G and H). Based on the spatial distribution of the Shamuluo Formation, namely the main body to the north, with minor elements scattered throughout the suture zone, we tentatively concluded that a north dipping thrust fault separates the Shamuluo Formation from the Mugagangri Group.

The Shamuluo Formation is overlain by red beds (Fig. S5I). Eight kilometers to the west of Xiede Village (Fig. 2), the red beds are over 100 m thick and dipping north. Clast-supported massive and poorly sorted conglomerates occur in the lower part, with biggest gravels reaching 40 cm in diameter, indicating an alluvial fan environment. Imbricated and horizontally stratified conglomerates dominate the upper part, implying a braided river environment. All the conglomerates are dominated by limestone clasts, including oolitic grainstones, oncoidal rudstones (Fig. S5I), and bivalve framestones, implying that they are derived from the surrounding Shamuluo Formation.

4.2 Sandstone petrology

Sandstones from the Shamuluo Formation are litho-quartzose (with feldspar < 10% and quartz > lithic fragment > 10%, classification after Garzanti (2016); Figs. 6E and 6F), with twenty-four samples from both the Xiede and Najiangco sections yielding an average Q-F-L composition of 77:3:20 (Fig. 12). Quartz grains are mainly monocrystalline (97% of all quartz grains). Feldspar grains are less abundant in the Xiede section (average = 0.3%) than in the Najiangco section (average = 5%); in both sections, plagioclase is roughly twice as prevalent as potassium feldspar. Lithic fragments consist mainly of felsic volcanic grains, with subordinate metamorphic fragments and minor sedimentary detritus (average composition Lm-Ls-Lv = 22:9:69). The metamorphic fragments are composed mainly of schist, phyllite, slate and minor quartzite, and are more abundant in the Xiede section (average = 31% of total lithic fragments) than the Najiangco section (average = 15%). The sedimentary fragments generally consist of argillite and siltstone, though limestone fragments are abundant in two samples (16NJ13 and 16NJ34).

4.3 U-Pb ages of detrital zircons

Four samples (16XD13 and 16XD35 from the Xiede section, 16NJ13 and 16NJ24 from the Najiangco section) were collected for detrital zircon U-Pb dating. The zircon crystals are generally rounded to subrounded. The U-Pb age-spectra of Shamuluo Formation detrital zircons are generally similar for both sections, though some minor differences can be observed (Fig. 13). All four samples show discrete peaks at ~2500 Ma and ~1850 Ma, as well as peaks in the 1000-750 Ma, 450-420 Ma, and 300-210 Ma age ranges. In both sections, the youngest zircon ages are Late Triassic (Fig. 13). In the Xiede section, detrital zircon ages < 230 Ma are rare, with one isolated age of 223 ± 4 Ma near the base of the section (sample 16XD13), and one isolated age of 211 ± 3 Ma up-section (sample 16XD35). In the Najiangco section, the three youngest ages of 211 ± 3 Ma, 211 ± 3 Ma, and 227 ± 4 Ma (sample 16NJ12) occur low in the section, and there are more young ages of 211 ± 3 Ma, 218 ± 4 Ma, 220 ± 3 Ma, 222 ± 4 Ma, 224 ± 4 Ma, and 227 ± 5 Ma (sample 16NJ24) up-section.

4.4 U-Pb ages of porphyric granitoid intrusions

Two types of porphyric granitoid intrude into the Shamuluo Formation. The first type is pale green, and exhibits a porphyritic texture. It is exposed at three localities (32°14′31.98"N, 88°27′33.01"E; 32°14′32.23"N, 88°27′36.33"E; 32°17′55.14"N, 88°30′32.91"E). In the first and third location, the intrusion cuts across sedimentary bedding (Fig. 4M). In the second location, the intrusion parallels the bedding of the surrounding argillite (i.e., it is a sill). The second type of intrusion, found ~600 m southeast of the Najiangco section (32°14′33.61"N, 88°27′31.24"E), consists mainly of quartz and feldspar phenocrysts. In thin sections, both types of porphyric granitoid have a cryptocrystallize or microcrystalline felsic groundmass (Figs. 13A and B). The first type contains phenocrysts composed of feldspar, biotite, and quartz (Fig. 13A). The second type shows a spherulitic texture, and some quartz phenocrysts within it are embayed, possibly related to high-temperature magmatic corrosion (Fig. 13B).

Zircons in both types of porphyric granitoid are euhedral to subhedral. The crystals in the first type of intrusion are 30–120 μm in length, with length-to-width ratios 2:1 to 17:1; in the second type of intrusion, crystals are 50–150 μm in length, with length-to-width ratios 1:1 to 4:1. Zircons from both samples are high in Uranium content (Table S3), as suggested by their nearly black CL images. Zircons with slightly visible oscillatory zoning, instead of those that appear completely black in CL images, were preferentially analyzed for U-Pb dating, because most of the latter have discordant ages due to radiation damage and subsequent alteration (Gao et al., 2014).

Sixteen concordant analyses from the first intrusion type yield $^{206}Pb/^{238}U$ ages of 156 Ma to 145 Ma, with a weighted mean age of 150.8 ± 1.9 Ma (MSWD = 1.12) (Fig. 14C). Sixteen nearly concordant analyses from the second intrusion type yield $^{206}Pb/^{238}U$ ages of 122 Ma to 113 Ma, with a weighted mean age of 116.1 ± 1.8 Ma (MSWD = 0.44) (Fig. 14D).

5. Discussion

5.1 Age of deposition

The coral fossils collected from the Shamuluo Formation near the Xiede section, at Tukari locality, and at Aobao locality indicate a Late Jurassic (most likely Oxfordian-Kimmeridgian) depositional age (Figs. 6G, 6H, 6I, S1 and S2). The foraminifera (Fig. 11) in the Gaaco section indicate an Oxfordian (possibly) to Kimmeridgian depositional age. The porphyritic granitoids intruding into the Shamuluo Formation were dated at 150.8 Ma and 116.1 Ma, respectively, constraining the minimum depositional age (~150.8 Ma, Late Jurassic). Combining these data, we suggest that the Shamuluo Formation was deposited during the Oxfordian-Kimmeridgian (164 - 152 Ma), when corals were important reef-building organisms (Scott, 1988). These age constraints are consistent with former studies in three ways. First, earlier biostratigraphic studies based on corals, stromatoporoids, chaetetids, and brachiopod fossils (Fan et al., 1987; Institute of Tibetan Geological Survey, 2006a; Ji et al., 2011; Liao et al., 2012) have suggested that the Shamuluo Formation was deposited during the Late Jurassic. Second, the Kangqiong granodiorites intruding into the Shamuluo Formation were dated at 147.6 – 149.9 Ma (Li et al., 2016), suggesting the depositional age is older than 150 Ma. Third, the Shamuluo Formation in the northern Nima Basin was deposited prior to the Early Cretaceous, by which time the area had become highlands that produced sediment for Early Cretaceous continental red beds to its south (DeCelles et al., 2007).

We cannot exclude the possibility that Shamuluo Formation deposition may extend into Early Cretaceous time along strike. In the Dongqiao area, ~ 130 km to the east of our field area, Chen et al. (2004) designated an Early Cretaceous age for the corals *Stylosmilia* and *Stylina* in the Shamuluo Formation. Orbitolinids (larger benthic foraminifera) of Early Cretaceous age have been reported from 150 km west of Nima (Liao et al., 2006), and from further west, near Ritu (Xie et al., 2010). In addition, the youngest detrital zircons reported from the Shamuluo Formation in the Gaize area, ~400 km west to our studied area, are Early Cretaceous in age. Huang et al. (2016) reported detrital zircon dating results from three samples, one of which (sample 09GZ12) yielded youngest zircon grain ages at 139 Ma, 135 Ma, 134 Ma and 113 Ma. Li et al. (2017a) reported one sample (2013TF40) from the upper part of the Shamuluo Formation that yielded two youngest detrital zircon ages of 153 Ma and 143 Ma.

5.2 Sediment provenance

The sandstones of the Shamuluo Formation in the Najiangco area are litho-quartzose and contain an assemblage of lithic detritus dominated by volcanic and metamorphic grains, as well as minor sedimentary fragments (Fig. 12). This indicates a recycled orogenic provenance (Dickinson, 1985), which experienced intermediate to felsic volcanism and variable grades of metamorphism, as suggested by slate, phyllite, schist, and quartzite detritus. Sandstone compositions in the Shamuluo Formation are similar to those in the upper unit of the early Callovian Biluoco Formation, north of the studied area (Ma et al., 2017) (Fig. 12).

The detrital zircon age-spectrum of the Shamuluo Formation is also similar to that of the upper Biluoco Formation which shows a recycled orogeny provenance (Fig. 12), as well as to pre-Jurassic strata in Qiangtang; it is notably different from the age spectra seen in pre-Jurassic strata of the Lhasa Block (Fig. 13). Thus, the Shamuluo Formation was sourced from a recycled orogen in the Qiangtang interior. The youngest zircons in the Shamuluo Formation are Late Triassic in age. For this reason, the Bajocian Sewa Formation in the southern

Qiangtang Basin, containing Qiangtang arc detritus characterized by Jurassic zircons (Ma et al., 2017), can be ruled out as the source.

5.3 Late Mesozoic paleogeography

Our reconstruction of the paleogeography of the southern Qiangtang from Jurassic through Early Cretaceous time can be divided into four stages (Fig. 15). Stage 1: During the Early to Middle Jurassic, the southern Qiangtang was characterized by coastal and shelf environments deepening southward, with limestone and clastic rocks deposited alternately (Ma et al., 2017) (Figs. 3 and 15A). The coast of the southern Qiangtang Basin was along the central Qiangtang area in east-west direction, which was a non-depositional area (maybe drowned during the Bathonian) separating the northern and southern Qiangtang Basin (Ma et al., 2017; Wang and Fu et al., 2018) (Fig. 15A).

Stage 2: The fan delta conglomerates and sandstones of the Biluoco Formation were deposited during the late Middle Jurassic (late Bathonian to early Callovian), with the coast located near the central Qiangtang (Ma et al., 2017) (Fig. 15B). The shallow-marine limestones of the Callovian Suowa Formation were deposited conformably overlying the Biluoco Formation (Ma et al., 2017; Yin, 2016), and represent the youngest marine strata in the northern part of the southern Qiangtang (Fig. 15B). Early Cretaceous foraminifera from marine succession have been reported ~140 km northeast of the Najiangco area (Zhang et al., 2002), however, are enigmatic as the GPS coordinates provided (~32°50′N, 90°12′E) are plotted included in the Upper Triassic strata in the southern Qiangtang Basin (Institute of Tibetan Geological Survey, 2003).

Stage 3: During the Late Jurassic (Oxford - Kimmeridgian), when the Shamuluo Formation was deposited, the Najiangco area was in a sub-aerial to shallow-marine environment (Fig. 15C). The paleogeographic picture is less clear for the northern margin of the Najiangco region, because only the Xiede section was investigated. This northernmost section was in a tidal flat to subtidal lagoon environment, which was close to the coastline. In addition, the Late Jurassic marine strata of the Shamuluo Formation do not occur north of the Southern Qiangtang thrust (Fig. 1C), which implies that the trace of this fault may stop the sea water to further north. Further south, the Najiangco section, Aobao locality, and Jiarebuco section were in a delta front to prodelta environment, heavily influenced by terrigenous detrital input. We propose that rivers may have drained to this area during the Late Jurassic; a modern analogue might be the Great Barrier Reef off the northeastern coast of Australia (Larcombe et al., 2001). Along the southern margin of the Najiangco area, the limestone in the Tukari locality, Gaaco and Zumu sections contains no terrigenous siliciclastic materials, indicating a marine environment without terrigenous influence. The Shamuluo Formation in the Tukari locality contains patch reefs, while in the Gaaco and Zumu sections it is characterized by shoal and open platform environments. In a broader sense, to the north of Najiangco and Biluoco areas, marine environments in the northern Qiangtang Block may persist into the Late Jurassic as suggested by coral limestones (Sun et al., 2013).

Stage 4: During the Early Cretaceous (Fig. 15D), no marine sediments were deposited in the Najiangco area. To its south, the northern Nima area was above sea level by 118 Ma (Kapp et al., 2007), with red beds sourced from the Qiangtang highlands deposited during probably Aptian-Albian time (DeCelles et al., 2007; Kapp et al., 2007). Further to the south, the Early Cretaceous (mainly Aptian to Early Cenomanian) shallow-marine sandstones and limestones were deposited in the northern Lhasa region, with the Qiangtang Block as a provenance component (Leier et al., 2007; Sun et al., 2017). The latest marine strata are found in the Langshan Formation limestone, which may be as young as Early Cenomanian (Boudagher-Fadel et al., 2017).

5.4 Regression and uplift in the southern Qiangtang region

Based on our reconstruction of the paleogeography of the southern Qiangtang, two major stages of apparent regression occurred during Middle to Late Jurassic time. First, the Bangong-Nujiang remnant sea retreated southwards, from the northern part of the southern Qiangtang Block to its southern margin. This stage was in progress during the latest Middle Jurassic to earliest Late Jurassic, leading to a shallow-marine succession (the Shamuluo Formation) deposited in the southern Qiangtang remnant sea during Late Jurassic time, with the shoreline located just to the north of the Xiede section (Figs. 15B and 15C). This initial apparent marine regression (between the Callovian and Oxfordian) likely resulted from a regional tectonic event rather than global eustatic sea-level fall, as there was no significant eustatic sea-level change at that time (Hallam, 1988) (Fig. 3). During the second stage of regression, the sea retreated completely from the Najiangco area, some time between the deposition of the Shamuluo Formation (~152 Ma) and the deposition of the Aptian red beds (118 Ma) (DeCelles et al., 2007; Kapp et al., 2007) (Figs. 15C, D).

The successive southward propogation of topographic uplift in the southern Qiangtang corresponds to the evolution of sedimentary facies and the retreat of the sea. Three discrete episodes of uplift in the southern Qiangtang can be documented. The first episode began in the late Middle Jurassic, when the central Qiangtang region was lifted up and began shedding detritus into the Biluoco Formation fan delta (Ma et al., 2017) (Fig. 15B). The second episode occurred during the latest Middle Jurassic, after deposition of the Suowa Formation and prior to deposition of the Shamuluo Formation (Figs. 15B and C). This period of uplift was not intense, and none of arc materials (Sewa Formation with 183-170 Ma zircons ref. Ma et al., 2017) that are abundant in the Jurassic strata of the Qiangtang Basin were recycled into the Shamuluo Formation. As a result of this stage, the sea was confined to the southern margin of the Qiangtang Basin. The third episode of uplift happened after the deposition of the Shamuluo Formation (153 Ma), but prior to deposition of the Early Cretaceous Nima red bed (Kvc unit)

(Kapp et al., 2007) (Figs. 15C and D). This marks the wide-spread uplift of the Qiangtang region and Bangong-Nujiang suture zone, which began shedding detrital materials into the northern Lhasa basin during the Early Cretaceous (Kapp et al., 2007; Leier et al., 2007).

The successive propogation of south-vergent thrust belts might be responsible for the topographic uplift. Three Cenozoic thrusts, including the Zadaona-Riganpei Co thrust system, the Southern Qiangtang thrust and the Shiquanhe-Gaize-Amdo thrust system, were identified in previous studies (Institute of Tibetan Geological Survey, 2006a, b; Kapp et al., 2005) (Fig. 1B). However, whether they were active during Jurassic time is not yet clear.

5.5 Tectonic implications

Based on our field observations in few sites (Fig. S5), the Shamuluo Formation is interpreted to be in fault contact with the Mugagangri Group along the southern margin of the Najiangco area. However, the original nature of this contact is debatable, with two basic possibilities:

(1) The Shamuluo Formation was originally deposited overlying the Mugagangri Group. In this scenario, the subduction prism of the Mugagangri Group would have grown or been uplifted from a deep-marine to a very shallow-marine between the Early-Middle Jurassic (Huang et al., 2017; Li et al., 2017a; Ma et al., 2017) and the Late Jurassic. An angular unconformity between the Shamuluo Formation and the Mugagangri Group has been the traditional interpretation of this contact (e.g., Huang et al., 2017; Institute of Tibetan Geological Survey, 2006a; Li et al., 2017a) and tentatively attributed to the initial Lhasa-Qiangtang collision (Li et al., 2017b). In a broader sense, the interpreted unconformity may be correlated with the contact between the Dongqiao Formation and underlying ophiolite in Dongqiao area, which was attributed to ophiolite obduction due to Lhasa-Qiangtang collision (Girardeau et al., 1984).

(2) The Shamuluo Formation was originally in fault contact with the Mugagangri Group. In this scenario, the Shamuluo Formation was originally deposited in the southern Qiangtang Basin and thrusted into the Bangong-Nujiang suture zone over the Mugagangri Group. Additional field work is needed to further investigate the contact.

The youngest zircon age peak (220-210 Ma) in the Shamuluo Formation is much older (over ~45 Myr) than the depositional age (Oxfordian-Kimmeridgian) (Fig. 13), which implies that in the Late Jurassic, the southern Qiangtang Basin was either an extensional or continental collisional basin (Cawood et al., 2012). The continental collisional basin interpretation is favored, as the southern Qiangtang experienced continuous shortening and topographic uplift instead of extension during Late Jurassic to Early Cretaceous time (Kapp et al., 2007; Raterman et al., 2014; Zhao et al., 2017). The collisional basin in the southern Qiangtang may have initiated as early as the late Middle Jurassic, as implied by at least ~45 Myr gap between the youngest detrital zircon age peak and the depositional age of the Biluoco Formation (Ma et al., 2017) (Fig. 13).

This collisional basin experienced continuous evolution during the late Middle to Late Jurassic. Both the Biluoco and Shamuluo formations were deposited in subaerial to shallow-marine environments, with sediments sourced from the central Qiangtang recycled orogen (Fig. 3). However, they differ in their depositional location and age. The Biluoco Formation was deposited on the proximal flank of the recycled orogen, during early Callovian time, while the Shamuluo Formation was deposited further south, along the southern margin of the Qiangtang Basin during Oxfordian to Kimmeridgian time (Fig. 3).

6. Conclusions

(1) The depositional age of the Shamuluo Formation in the Najiangco area is Late Jurassic (Oxfordian-Kimmeridgian), based on the coral and foraminifera biostratigraphy, and U-Pb dating (150.8 ± 1.9 Ma) of a porphyritic granitoid dike.

(2) The Shamuluo Formation is composed of sandstone, limestone, siltstone, and shale, deposited in peritidal to shallow-marine environments. Peritidal and deltaic facies with mixed siliciclastic and carbonate deposits predominate in the northern part of the Najiangco area. Limestones deposited in carbonate shoals and patch reefs dominated its southern margin.

(3) Detrital composition in sandstones from the Shamuluo Formation implies provenance in a recycled orogen. The age spectra of detrital zircon show an affinity with the Qiangtang Block, and the youngest population at 220-210 Ma is ~45 Myr older than the depositional age, implying that the source area was in the Qiangtang interior to the north of the basin.

(4) The residual sea in the southern Qiangtang Basin retreated southwards during late Middle to Early Cretaceous time; meanwhile, topographic uplift extended southwards from the Qiangtang interior to its southern margin.

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Figure and table captions

Figure 1. (A) Schematic tectonic outline of the Tibetan Plateau (adapted from Zhu et al., 2016). (B) Simplified geological map showing the Mesozoic geological mappable units along the Bangong-Nujiang suture zone (adapted from Zhu et al., 2016). (C) Simplified geological map

of the Najiangco to Amdo areas in central Tibet (adapted from Institute of Tibetan Geological Survey, 2002, 2003, 2005a, b, 2006a, b). JSSZ: Jinsha suture zone; BNSZ: Bangong-Nujiang suture zone; NQ: northern Qiangtang; SQ: southern Qiangtang; IYSZ: Indus-Yarlung suture zone; ZRT: Zadaona-Riganpei Co thrust system; SQT: Southern Qiangtang thrust; SGAT: Shiquanhe-Gaize-Amdo thrust system.

Figure 2. Geologic map of the Najiangco area (modified from Institute of Tibetan Geological Survey, 2006a, b), showing measured sections and sampling sites in the Shamuluo Formation.

Figure 3. Stratigraphic correlation chart for the Biluoco area and Najiangco area in the southern Qiangtang Basin, and the Northern Nima and Selingco area in the Bangong-Nujiang suture zone.

Figure 4. Outcrop photographs: (A) full view of the Shamuluo Formation, Xiede section (32°28′27.39"N, 88°39′07.95"E); (B) litho-quartzite with argillite intraclasts and flaser beddings overlain by red limestone containing siliciclastic materials, Shamuluo Formation, lower part of Xiede section; (C) rhythmite composed of sandstone and argillite, Shamuluo Formation, lower part of Xiede section; (D) branched coral colony, Shamuluo Formation, upper part of Xiede section; (E) full view of the Shamuluo Formation, Najiangco section (32°28′27.39"N, 88°39′07.95"E); (F) lithological associations in the Shamuluo Formation, Najiangco section, showing resistant medium- to thick-bedded limestones and sandstones interbedded with recessive thin- to thick-bedded sandstones and argillites; (G) full view of the Shamuluo Formation, Gaaco section (32°12'4.86"N, 88°51'3.18"E); (H) full view of the Shamuluo Formation, Zumu section (32°5'56.60"N, 88°21'24.77"E); (I) oncoidal rusdstone, Zumu section; (J) full view of the Shamuluo Formation, Tukari locality (32°14'4.84"N, 89°10'11.15"E), showing reef assemblage; (K) full view of the Shamuluo Formation, Jiarebuco section (32°10'21.60"N, 87°43'19.85"E), showing argillite intercalated with sandstone; (L) branched coral fossils, Shamuluo Formation, Aobao locality (32°49'33.10"N, 88° 24'32.70"E);

(M) pale green porphyritic granitoid dike (150.8 ± 1.9 Ma) in the Shamuluo Formation, ~600 m southeast of Najiangco section (32°14′31.98"N, 88°27′33.01"E).

Figure 5. Stratigraphic column showing the Shamuluo Formation in the lower part of the Xiede section.

Figure 6. Photomicrographs in thin sections: (A) argillite intraclast, 16XD05, lower part of Xiede section; (B) mixed carbonate and siliciclastic matrix between corals, 16XD15, lower part of Xiede section; (C, D) bioturbated siltstones, 16XD22 and 16NJ37, from the lower part of Xiede section and Najiangco section, respectively; (E, F) litho-quartzose sandstones, 16XD09 and 16NJ04, from the lower part of Xiede and Najiangco sections, respectively (Qm, monocrystalline quartz; Qp, polycrystalline quartz; Lm, metamorphic lithic fragments; Lv, volcanic lithic fragments); (G) coral speceis *Thecosmilia* cf. *dichotoma* Koby (J_3), 16XD55, upper part of Xiede section; (H) coral speceis *Cladophyllia conybearei* Milne-Edw. & Haime (J_3), 16SL28, Tukari locality; (I) coral speceis *Thecosmilia dichotoma* Koby (J_3), 16NJ59, Aobao locality.

Figure 7. Photomicrographs of typical microfacies in the upper Xiede section (A-D) and in the Gaaco section (E-H): (A) MF1, fine to very fine-grained sandstone with couplets of sandstone and argillite, 16XD36; (B) MF2, oolitic grainstone with scattered detrital fragments, with some serving as nuclei of ooids, 16XD33; (C) MF3, muddy siltstone, 16XD37; (D) MF4, bioclastic floatstone with siliciclastic detritus, 16XD54; (E) MF5, oncoid rudstone, 15GA01; (F) MF6, oolitic grainstone, 15GA20; (G) MF7, bioclastic wackestone, 15GA89; (H) MF8, bivalve framestone, 15GA59.

Figure 8. Stratigraphic distribution of microfacies in the Shamuluo Formation, upper part of the Xiede section.

Figure 9. Stratigraphic column of the Shamuluo Formation in the Najiangco section.

Figure 10. Stratigraphic distribution of microfacies in the Shamuluo Formation, Gaaco section.

Figure 11. Benthic foraminifera in limestones of the Gaaco sections. (A) *Siphovalvulina* sp., 15GA55; (B) *Pseudocyclammina lituus* (Yokoyama), 15GA81; (C) *Involutina* sp., 15GA65; (D-E) *Mesoendothyra izumiana* Dain, 15GA95; (F) *Lituosepta* sp., 15GA92; (G-H) *Everticyclammina virguliana* (Koechlin), G) oblique section through the rectilinear part of the test, 15GA65; H) 15GA81; (I) *Rectocyclammina chouberti* Hottinger, 15GA92; (J) *Andersenolina elongata* (Leupold), 15GA65; (K) *Cladocoropsis mirabilis* Felix, 15GA27. Scale bars: A-I = 0.25 mm; J-K = 1 mm. Sample horizons on the measured Gaaco section can be found in Fig. 10.

Figure 12. Ternary diagrams for detrital composition of sandstones from the Shamuluo Formation, compared with that from the upper Biluoco Formation (Data from Ma et al., 2017). Q, quartz; F, feldspar; L, lithic fragments (Lm, metamorphic; Ls, sedimentary; Lv, volcanic).

Figure 13. U-Pb age–probability density diagrams for detrital zircons from sandstones of the Shamuluo Formation. Detrital zircon U-Pb age data from pre-Jurassic strata in the southern Qiangtang Basin (Dong et al., 2011; Gehrels et al., 2011; Ma et al., 2017; Pullen et al., 2011; Wang et al., 2016), pre-Jurassic strata from the Lhasa Block (Gehrels et al., 2011; Leier et al., 2007; Li et al., 2014a; Wang et al., 2016; Zhu et al., 2011), and the late Middle Jurassic upper Biluoco Formation in the southern Qiangtang Basin (Ma et al., 2017) are plotted for comparison.

Figure 14. Photomicrographs in thin sections and geochronological results of porphyritic granitoid dikes in the Shamuluo Formation, near the Najiangco section. (A) and (C): 16NJ41 (32°17'55.14"N, 88°30'32.91"E); (B) and (D): 16NJ40 (32°14′33.61"N, 88°27′31.24"E).

Figure 15. Schematic paleogeographic map of the Najiangco and adjacent areas during Jurassic to Early Cretaceous time. (A) During the Early to Middle Jurassic, the southern Qiangtang

(Biluoco-Najiangco) deepened southward, and the northward transgression across central Qiangtang high topography might connect the northern Qiangtang sea (Ma et al., 2017; Wang and Fu et al., 2018); (B) During the late Middle Jurassic, the central Qiangtang area was uplifted and recycled to supply detritus to the southern Qiangtang Basin, with the fan delta of Biluoco Formation formed; then marine transgression resulted in the deposition of Suowa Formation limestone (Ma et al., 2017); (C) During the Late Jurassic, the northern part of the southern Qiangtang (Biluoco area) had been uplifted and the shallow sea only prevailed on the southern margin of Qiangtang Block (Najiangco area); (D) During the Early Cretaceous, the southern Qiangtang and Bangong-Nujiang suture zone had been uplifted and remnant sea in the southern Qiangtang had disappeared, with northern Lhasa sea prevailing (Decelles et al., 2007; Leier et al., 2007; Sun et al., 2017). Scale is based on current location, with shortening not considered.

Figure S1. Coral fossils in the Shamuluo Formation. Specimens 16XD12-55 are from the Xiede section, 16SL28-39 are from Tukari locality. *Cladophyllia minor* Beauvais (J_3): 16XD12, 16XD19, 16XD20; *Thecosmilia minuta* Koby (J_3): 16XD31, 16NJ60; *Thecosmilia* ? sp. (J-K): 16XD45, 16SL34, 16SL35, 16SL37; *Cladophyllia* sp. (J-K): 16XD15; *Thecosmilia dichotoma* Koby (J_3): 16XD39, 16NJ58 and 16NJ59; *Thecosmilia* cf. *dichotoma* Koby (J_3): 16XD55; *Thecosmilia trichotoma* (Goldfuss) (J_3): 16NJ57; *Fungiastraea arachnoides* (Parkinson) (J_3):16NJ63; *Cladophyllia dichotoma* (Goldfuss) (J_3): 16SL38; *Cladophyllia* cf. *excelsa* (Koby) (J_3):16SL39; *Cladophyllia conybearei* Milne-Edw. & Haime (J_3): 16SL28; *Stylina* ? sp. (J): 16SL29; *Stylina bangoiensis* Liao & Xia (J_3): 16SL30; *Thecactinastraea krimensis* Turňsek (J_3): 16SL32. The bar is 1 cm.

Figure S2. Coral fossils from the Shamuluo Formation at the Aobao locality. For identification results, see the caption for Figure S1.

Figure S3. Stratigraphic column showing the Shamuluo Formation in the Jiarebuco section.

Figure S4. The Zumu section, featuring interbedded oncoidal rudstone and oolitic grainstone.

Figure S5. Photographs of stratigraphic contacts in outcrops: (A) north-dipping limestone of the Shamuluo Formation with intercalated basalt, three kilometers west of Gaaco section (32°10'19.37"N, 88°49'45.06"E). Contact between limestone and basalt is interpreted to be a fault; (B, C, D) boundary between mountains of north-dipping Shamuluo Formation limestone and lowlands of Mugagangri Group siliciclastic rocks, photographed in three locations in the studied area (respectively: 32°15'58.27"N, 89°15'37.89"E; 32°15'16.06"N, 89°14'21.04"E; 32°4'50.76"N, 88°24'30.19"E). Contact between Shamuluo Formation and Mugagangri Group is interpreted to be a fault. Five-pointed star in Fig. S5B refers to the location of the close-up shown in Fig. S5E; (E) limestone breccia, at the contact shown in Fig. S5B; (F) limestone breccia, north of Selingco (32°10'30.76"N, 89°02'32.20"E); (G) coral bearing limestone in the suture zone (32°10'06.97"N, 89°24'13.36"E); (H) close-up of coral thicket in Fig. S5G; (I) red beds overlying the limestone of the Shamuluo Formation, eight kilometers west of Xiede Village (32°07'34.50"N, 88°34'2.22"E); (J) oncoidal rudstone cobble in the red beds show in Fig. S5I.

Table S1. Summary of corals, brachiopods, stromatoporoids, chaetetids, and foraminifera reported from the Shamuluo Formation.

Table S2. Gazzi-Dickinson point-counting data for sandstones from the Shamuluo Formation.

Table S3. Measured U-Pb isotopic ratios and ages of sandstones from the Shamuluo Formation and of porphyritic granitoids cutting the Shamuluo Formation.

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