Initial growth of the Northern Lhasaplano in the early Late Cretaceous (93-87 Ma)

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ABSTRACT

Constraining the stepwise growth of the Tibetan Plateau in time and space is critical to test geodynamic models of subduction and continental collision, as well as environmental and climatic changes at the regional and global scale. The Lhasa block is a key region to unravel the early stages of Tibetan Plateau growth before the India-Asia collision. Stratigraphic, sedimentological, geochronological, and provenance analysis of the Jingzhushan Formation in the northern Lhasa block and of the Daxiong Formation in the central Lhasa block provide new information to reconstruct the paleogeographic evolution of the central part of the Tibetan Plateau during the Cretaceous. Sharply distinct from the underlying shallow-marine limestones, the over 1000-m-thick Jingzhushan and Daxiong formations mainly consist of conglomerates and coarse-grained sandstones deposited in alluvial-fan and braided-river systems. Both units were deposited during the early Late Cretaceous between ca. 93 and 87 Ma, as determined by geochronology of interstratified tuff layers, youngest ages of detrital zircons, and micropaleontological data from limestone pebbles. Clast composition, U–Pb ages and Hf isotopic signatures of detrital zircons, and paleocurrent data indicate that the Jingzhushan and Daxiong formations were derived from the same elevated source area located in the central-northern Lhasa block. These two parallel belts of coeval conglomerates record a major change in topography of the source region from a shallow seaway to a continental highland, implying initial topographic growth of an area over 80,000 km^2 wide named here the Northern Lhasaplano. Early Late Cretaceous topographic growth of the Northern Lhasaplano was associated with demise of seaways, development of thrust belts, and thickening of the lower crust. The same paleogeographic and paleotectonic changes were recorded earlier in the Northern Lhasaplano than in the Southern Lhasaplano, indicating progressive topographic growth from north to south across the Bangong-Nujiang suture zone and Lhasa tectonic domain during the Cretaceous.

KEYWORDS: Jingzhushan Formation; Daxiong Formation; Northern Lhasaplano; Late Cretaceous; Provenance; Topographic growth, Tibetan Plateau

1 INTRODUCTION

The Tibetan Plateau, the world's highest and widest plateau, with an average elevation >5000 m (Fig.1a), has a major effect on the development of the Asian monsoon and global climate change, ocean chemistry, and regional species distribution (Raymo and Ruddiman, 1992; An et al., 2001; Dupont-Nivet et al., 2007; Deng et al., 2011). Constraining the surface-uplift history of the Tibetan Plateau and its timing is not only crucial to tune paleoclimatic and paleoceanographic models, but offers a key testing ground for theories of plateau growths by crustal thickening (Dewey and Burke, 1973), delamination of lower lithosphere (Molnar et al., 1993), channel flow (Rodgers and Schwartz, 1997; Royden et al., 1997; Harris, 2007), or other tectonic mechanisms (Tapponnier et al., 2001). Early studies of the Tibetan region suggested that plateau uplift resulted from continuous thickening and widespread viscous flow of the underlying crust and mantle contribute the uplift of the Tibetan Plateau (Dewey and Burke, 1973). Based on petrogenetic analysis of K-rich magmatic rocks, Chung et al. (1998) concluded that surface uplift of the plateau did not occur earlier than 40 Ma in the east, and than 20 Ma in the west. More recently, based on various tectonic and paleoelevation evidence, Wang et al. (2008) suggested that the plateau grew both northward and southward, starting from an elevated proto-plateau in the Late Paleogene. A wide consensus has been reached that most of the Tibetan Plateau existed in the Paleogene, and that the present elevation was attained in multiple steps recorded at different time in different regions (Chung et al., 1998; Rowley and Currie, 2006; Wang et al., 2008, 2014a; Xu et al., 2015; Wei et al., 2016; Chen et al., 2017). The modality and timing of surface uplift, however, have remained unclear.

The Lhasa block represents a large part of the Tibetan Plateau. Stable isotope results from lacustrine carbonates have revealed that the Linzhou and Namling basins surrounding the Gangdese Mountains (Spicer et al., 2003; Currie et al., 2005; Ding et al., 2014) have maintained an elevation above than 4500 m since the India-Asia collision, and that the northern Lhasa block reached at least 4000 m during the Oligocene (Rowley and Currie, 2006; DeCelles et al., 2007b). Low-temperature thermochronology reveals that the Lhasa block experienced rapid to moderate cooling and exhumation by Late Cretaceous time (85-70 Ma; Hetzel et al., 2011). Structural restorations indicate that more than 50% crustal shortening of the Lhasa block took place during the Cretaceous (Murphy et al., 1997; Kapp et al., 2007a, 2007b; Volkmer et al., 2007), leeding to speculate that there is a "Lhasaplano” developed before the India-Asia collision (Kapp et al., 2005, 2007a). Arguing for the Cretaceous “Lhasaplano”, Wang et al. (2008) proposed that surface uplift of the proto-Tibetan Plateau (Lhasa and southern Qiangtang blocks) took place at 40 Ma, based primarily on stratigraphic and thermochronological data. In addition, the occurrence of a spectacular angular unconformity separating strongly folded Cretaceous and older strata of the Lhasa block from the overlying, weakly deformed uppermost Cretaceous to lower Cenozoic Linzizong volcanic rocks, led to infer a contractional (Cordilleran-style) orogenic episode related to the Gangdese arc (Burg and Chen, 1983; England and Searle, 1986). Palaeo-altimetry data, rock exhumation, and crustal shortening record different processes related to the surface uplift, but the integration of such information with stratigraphic data to constrain the paleo-topographic evolution of the Lhasa block in space and time, and to corroborate or falsify the pre-collisional growth of a “Lhasaplano” during a Cordilleran-style tectonic event contractional orogeny, has never been carried out so far.

In this article we illustrate sedimentological evidence for uplift and erosion in the central-northern Lhasa block, and carry out detailed multi-technique provenance analysis based on gravel composition, sandstone petrology, palaeocurrent directions, detrital zircon U-Pb ages and Hf isotopes. Our aim is to constrain the timing of deposition of non-marine Upper Cretaceous strata and their spatial distribution, in order to determine pre-collisional surface uplift of the Lhasa block in space and time.

2 GEOLOGICAL BACKGROUND

2.1 Regional setting

The Tibetan Plateau was formed by the progressive accretion of a series of continental blocks (Fig. 1a) (Allègre et al., 1984; Dewey et al., 1988; Yin and Harrison, 2000), including the Lhasa block in the south and the Qiangtang block in the north, welded along the Bangong-Nujiang suture zone (BNSZ) (Fig. 1a).

The Lhasa block (Fig. 1a) can be subdivided into southern, central, and northern terranes, separated by the Shiquanhe-Nam Co Mélange Zone and by the Luobadui-Milashan Fault, respectively (Zhu et al., 2009). The southern Lhasa terrane is characterized by the Late Triassic to Paleogene Gangdese intrusive rocks, yielding zircons with positive εHf(t) >+ 10 (Chu et al., 2006; Ji et al., 2009; Zhu et al., 2011b; Dong et al., 2014). Corresponding volcanic rocks include the Jurassic Yeba Formation (Zhu et al., 2008), the Upper Jurassic to Lower Cretaceous Sangri Group (Kang et al., 2014), and the Paleogene Linzizong Group (He et al., 2007). Along the southern margin of the Gangdese magmatic arc, a thick succession of deep-water turbidites were deposited in the Xigaze forearc basin between the Albian and the Santonian (Dürr, 1996; Wang et al., 2012; An et al., 2014; Orme and Laskowski, 2016). The central Lhasa terrane includes a Precambrian crystalline basement (Dewey and Burke, 1973; Allègre et al., 1984), very-low-grade Carboniferous metasediments, Permian limestones, and Jurassic siliciclastic successions (Leeder et al., 1988; Yin and Li, 1988). The volcano-sedimentary Zenong Group, yielding zircons with negative εHf(t), accumulated during the Early Cretaceous (Zhu et al., 2009), whereas the non-marine Daxiong Formation was deposited in the Coqen basin during the Late Cretaceous (Sun et al., 2015b). The northern Lhasa terrane comprises more than 4 km of Upper Jurassic to Lower Cretaceous strata (XZBGM, 1993). Lower Cretaceous marginal-marine and deltatic clastic sediments, interbedded with the volcanic tuffs (Zhang et al., 2004; Leier et al., 2007a, 2007b; Volkmer et al., 2007; Zhang et al., 2012b), are overlain by the *orbitolina*-bearing limestone of the Aptian-Cenomanian Langshan Formation (Leier et al., 2007b; Scott et al., 2010; Rao et al., 2015; BouDagher-Fadel et al., 2017), and in turn by continental deposits of the Upper Cretaceous Jingzhushan Formation (DeCelles et al., 2007a; Kapp et al., 2007b; Zhang et al., 2012b). Cretaceous volcanic Qushenla Formation and related plutonic rocks also occur (Zhu et al., 2011b).

The Bangong-Nujiang suture zone (BNSZ) to the north (Fig. 1b) can be traced for at least 1200 km along the east-west strike of the range, and includes Jurassic deep-sea turbidites (Girardeau et al., 1984; Dewey et al., 1988; Li et al., 2017), mélange (Lai et al., 2017), and ophiolite fragments (Wang et al., 2016). Mid-Cretaceous to Cenozoic fluvial sandstones and conglomerates with interbedded volcanic rocks occur in the northern Nima and Lunpola basins (XZBGM, 1993; Kapp et al., 2005, 2007b; DeCelles et al., 2007a).

The Qiangtang block, bounded to the south by the Bangong-Nujiang suture and to the north by the Jinsha suture, is divided into the northern and southern Qiangtang terranes either by the Longmu–Shuanghu suture zone (Li, 1987; Li et al., 1995; Wang et al., 2015) or by an axial metamorphic belt including blueschist-bearing Lower Jurassic mélange (Cheng and Xu, 1987; Kapp et al., 2000; Kapp et al., 2003b; Pullen et al., 2008; Zhang and Tang, 2009). In the southern Qiangtang terrane, Cambrian metasedimentary rocks intruded by Ordovician granites lie in tectonic contact with Carboniferous–Jurassic strata (Pullen et al., 2011). Widespread marine Jurassic sandstones and limestones (Kapp et al., 2003b; Zhang et al., 2012a) were intruded by intermediate–felsic rocks of Jurassic (150-170 Ma) and Cretaceous age (100-130 Ma) and yielding εHf(t) values ranging widely from – 22 to + 10 (Li et al., 2014c, 2014d; Liu et al., 2017). Limited east-west-trending exposures of Cretaceous strata and non-marine Cenozoic deposits occur (XZBGM, 1993; Kapp et al., 2005).

2.2 Cretaceous geology of the study area

The study area is located in the central-northern Lhasa block, where the Lower Cretaceous Zelong Group is widely exposed. These felsic-andesitic volcanic rocks with minor mafic products, erupted between 143 and 102 Ma, reach a thickness of 1000 m at least and yielded zircons with negative εHf(t) values (Zhu et al., 2006, 2009, 2011b).

Lower Cretaceous strata in both northern and central Lhasa terranes contain a basal clastic succession and an upper limestone unit (Yin and Li, 1988; XZBGM, 1993; Zhang et al., 2004). Lowermost Cretaceous clastic sediments are called Chumulong Formation in the south, where they overlie Jurassic limestone and shale with locallly interbedded volcanic tuff, and Duoni Formation in the north, where they consist of shallow-marine to deltaic shale and sandstone (Leeder et al., 1988; XZBGM, 1993; Zhang et al., 2004, 2012b; Leier et al., 2007b). The Duoni Formation or the Zelong Group volcanic rocks are overlain by limestone beds of the Langshan Formation, deposited during Aptian to Cenomanian age (ca. 120 - 93 Ma). The Langshan Formation is dominated by wackstone and packstone with abundant benthic foraminifera thriving in low-energy lagoonal to shallow reef environments (Yin and Li, 1988; XZBGM, 1993; Leier et al., 2007b; Scott et al., 2010; Rao et al., 2015; BouDagher-Fadel et al., 2017).

In section SE-N04, south of Daze Co (Nima area; Fig. 1b), instead, the Jingzhushan Formation overlies a ~500-m-thick, clast- or matrix-supported cobble to boulder volcaniclastic conglomerate (Kcv unit; Fig. 3) having a maximum depositional age of 97 ± 2 Ma (DeCelles et al., 2007a; Kapp et al., 2007b). Beds are up to 20 m-thick and intercalated with minor lenses of coarse sandstone. Angular to subangular, very poorly sorted volcanic clasts mostly range from 1 to 20 cm in diameter (lithofacies Gcm, Gmm). Clast imbrication indicates roughly southward paleocurrents. Deposition by viscous debris flows on a proximal fan fed from to an elevated source area in the north was thus inferred.

The Jingzhushan Formation, unconformably overlying or in fault contact with Lower Cretaceous strata is a coarse and thick non-marine conglomerate unit with minor red sandstone and siltstone (Pan et al., 2004; DeCelles et al., 2007a; Volkmer et al., 2014; Sun et al., 2015b), exposed along a several km wide and >1000 km-long east-west-trending belt on the northern perimeter of the Lhasa block from Biru, Bangion, and Nima to west of Ritu (Fig. 1b). The depositional age of the Jingzhushan Formation was poorly constrained by Late Cretaceous detrital-zircon ages and Aptian-Albian limestone clasts containing *Orbitolina* (Ma, 2003; Kapp et al., 2007b). The broadly time-equivalent Daxiong Formation, exposed along a~10 km wide and ~700 km-long east-west-trending belt extending in the southern part of the central Lhasa block from the Coqen basin to the Nam Co (Fig. 1b; Murphy et al., 1997; Liu et al., 2004), includes red volcaniclastic conglomerates deposited at Cenomanian-Turonian times (96 – 91.5 Ma; Sun et al., 2015b).

These two non-marine conglomeratic units, also called as the Upper Cretaceous Conglomerate unit in the southern Nima Basin（Kuc unit of DeCelles et al. (2007a) or Kcl unit of Kapp et al. (2007b)), or Lajiangshan Formation in Nam Co by Chen et al. (2012), are unconformably overlain by Cenozoic Linzizong volcanic rocks and continental redbeds.

2.3 Cretaceous tectonics in the study area

Cretaceous deformation in the central-northern Lhasa block is documented by doubly-vergent thrusts (Murphy et al., 1997; Kapp et al., 2007b; Volkmer et al., 2014). The N-dipping Gugu La thrust (Fig. 1b) placed the Lower Cretaceous Zelong volcanic rocks over Cretaceous strata between 99 and 92 Ma, as documented by by cross-cutting granites (Murphy et al., 1997). The coeval S-dipping Gaize-Selin Co thrust (Fig. 1b) transported the Langshan Formation in its hanging wall, with conglomerates deformed into a northward-verging overturned syncline in the proximal footwall (Kapp et al., 2007b).

Crustal thickening and 46-60% N-S shortening took place on the central-northern Lhasa block during the Cretaceous to Paleogene, as indicated by structural analysis and regional mapping in Linzhou (Kapp et al., 2007a), Duba (Volkmer et al., 2014), Nima (Kapp et al., 2007b), Coqen (Murphy et al., 1997), Xiagangjiang (Volkmer et al., 2007), and Shiquanhe regions (Kapp et al., 2003a).

3 METHODS

3.1 Sedimentology and petrography

We measured detailed stratigraphic sections at 7 localities (sites shown in Fig.1b), and identified sedimentary structures, limestone microfacies, and depositional environments by a thorough investigation of lithofacies associations following criteria defined in Mial (1978, 1996) and DeCelles et al. (1991). Palaeocurrent directions were measured in the field from oblique lamination in sandstone beds and clast imbrication in conglomerate beds. Results were corrected to the horizontal by standard stereonet techniques, and the average trough-axis orientation of each point was determined statistically on a stereographic plot of 15-20 trough limbs (method I of DeCelles et al., 1983).

The petrographic composition of 9 sandstone samples from the Daxiong Formation and of 33 samples from the Jingzhushan Formation was determined by counting were selected to do modal framework-grain analysis on thin sections.o Over 350 sand larger than 62.5 μm ggrains were counted at a random area forper thin each section following the Gazzi-Dickinson method (Ingersoll et al., 1984). The different lithologies of conglomerate clasts were identified in the field, and 50 clasts at least were counted at each site using a 10 x 10 cm grid. About 1800 conglomerate clasts were counted overall in measured sections of the Kcv, Jingzhushang (27 sites) and Daxiong units (3 sites); the results are shown as pie charts (Fig. 3, Appendix Table S1).

3.2 Detrital zircon dating and Hf isotopes

Detrital zircons were separated from medium-grained sandstones of the Daxiong Formation. U-Pb dating was conducted by LA-ICP-MS at the State Key Laboratory of Mineral Deposits Research, Nanjing University, China, following the method described by Jackson et al. (2004). To avoid grain-to-grain bias and treat all samples equally, the laser spot was always placed in the rim of zircon grains and no cathodoluminescence

(CL) imaging was performed. The results were calculated by GLITTER 4.4 (Van Achterbergh et al., 2001) and common Pb corrections (Andersen, 2002) were made. The interpretation of zircon ages was based on ^{206}Pb/^{238}U ages for grains younger than 1000 Ma and on ^{207}Pb/^{206}Pb ages for grains older than 1000 Ma (Griffin et al., 2004). Zircon grains with discordance < 10% were considered valid. Age calculations and concordia diagrams were created using Isoplot 3.23 (Ludwig, 2001).

In-situ Hf isotopic analyses on detrital zircons yielding U-Pb ages younger than 250 Ma were carried out to constrain their provenance. Hf isotopic compositions were obtained by Thermo Scientific Neptune Plus (MC-ICP-MS) coupled with a New Wave UP193 solid-state laser ablation system (LA) at the State Key Laboratory of Mineral Deposits Research, Nanjing University. Zircon grains were ablated with a beam diameter of 35 μm with an 8-Hz laser repetition rate, and with an energy of 15.5 J/cm^2. Results were calculated assuming 1.865×10^{-11} a^{-1} for the decay constant of ^{176}Lu (Scherer et al., 2001). The $\varepsilon_{Hf}(t)$ values and Hf crust model age (T^{C}_{DM}) were calculated, following Bouvier et al. (2008) and Griffin et al. (2002), respectively.

Overall, we dated 670 detrital zircons in 9 sandstone samples from 5 sections of the Jingzhushan Formation and 225 detrital zircons in 3 samples from the Daxiong Formation (sampling sites shown in Fig. 3); 863 concordant ages and 384 Hf isotopic data from zircons younger than 250 Ma were obtained (Fig. 9, Fig. 10; Appendix Tables S3 & S4).

4. Kcv UNIT AND JINGZHUSHAN FORMATION

4.1 Sedimentology and stratigraphy

The >1000 m-thick Jingzhushan Formation, separated from the underlying Langshan Formation by the Gaize-Seling Co Thrust in sections SE-N02 and SE-N03, comprises red sandstone and conglomerate showing both fining- and coarsening-upward sequences (Fig. 3, 4b, 4c). Mottled conglomerate beds range 2-5 m in thickness and may include lenses of coarse sandstone (~20-50 cm). Fining-upward sequences may be up to 50 m-thick. Clasts are angular to subrounded and range mostly from 10 to 30 cm in diameter although some reach 1 m in size. Conglomerates, mostly clast-supported and poorly sorted, generally lack sedimentary structures (Fig. 4e, lithofacies Gcm), although cobble conglomerate beds may show crude horizontal bedding and grading, or clast imbrication (Fig. 4f, lithofacies Gch). Lenticular sandstones show mainly planar horizontal lamination (lithofacies Sp) or trough oblique lamination (lithofacies St).

Red sandstone beds, 30–200 cm thick and medium- to coarse-grained with sparse small pebbles at the base, show trough or planar oblique lamination (Fig. 4g, lithofacies St and Sp) and pass upward to medium-grained sandstones with plane-parallel lamination and rare current ripples (lithofacies Sh). Red laminated siltstone or mudrock may occur at the top of fining-upward sequences (Fig. 4h,lithofacies Fl). Several 20-50 cm thick tuff beds are intercalated with siltstone in section SE-N03 (Fig.3, 4h).

Rich information on paleocurrent directions obtained on trough-lamination and imbricated clasts indicate mostly northward paleoflows; some south-directed paleocurrent indicators were observed in sections SE-N01 and SE-N04.

4.2. Environmental interpretation

The structureless fabric, poor sorting, and dominant cobbles to boulders indicate that lithofacies Gcm consists of rock-avalanche deposits formed by rapid failure and accumulation close to the mountain front (Blair, 1999; Chen et al., 2017). The wide range of clast size, poorly organized texture, common erosional base, faint stratification and imbrication suggest rapid deposition from a highly concentrated sediment dispersion and high-magnitude flood flows in proximal fans (Naylor, 1980; Jo et al., 1997). Interbedded lenticular or wedge-shaped sandstones (lithofacies St and Sp) are considered as fluvial overbank to floodplain deposits close to the alluvial-fan channels. Fining-upward sandstone packages less than 2 m-thick and displaying trough or planar oblique lamination indicate deposition in shallow (< 2 m deep), unstable braided channels (Bristow, 1993; Miall, 1996). Siltstones or mudrocks (lithofacies F1) were sedimented during the the waning flow stages of overbank flow (Miall, 1996).

The Jingzhushan Formation, dominated by lithofacies Gcm, Gch, St, and Sp (Table 1) with fine sandstone (Sh and Fl) occurring only in discontinuous thin interbeds, accumulated in alluvial fans and gravelly braided channels adjacent to actively eroding highlands in the south. The unit can be subdivided into a lower sandstone and conglomerate member, a middle conglomerate member, and an upper sandstone and conglomerate member (Fig. 4a & c). The coarsening- and thickening-upward megasequence from the lower to the middle member indicates progradation from stream-flows and distal alluvial-fan to proximal alluvial-fan settings. The fining- and thinning-upward trend displayed by the upper member testifies to retrogradation and transition to distal alluvial-fan and braidplain environments.

4.3 Age constraints

The depositional age of these non-marine strata is constrained by the geochronological age of interbedded tuff layers, by the youngest ages of detrital zircons, by microfossils contained in limestone gravels, and by the age of intrusive granites. Twenty-seven zircon grains contained in tuffs intercalated between the middle and upper members yielded a single population with weighted average age of 92.2±0.8 Ma (Fig. 6, 15MT08). The youngest detrital zircon grains indicate the following maximum depositional ages of (samples ordered from east to west; Table 2): 91±4 Ma (13MD02); 92±2 (15QGC03); 91±1 Ma (15MT10); 92±3 Ma (15DZ25); and 90±3 Ma (13QR01). In addition, the youngest detrital zircons from the top of underlying Kcv unit suggest a maximum depositional age of 96 ± 1.6 Ma (15DZ35). Granites intruded into the

Jingzhushan Formation are dated as 80 ± 0.4 Ma (Fig. 6, 15BJ14).

Limestone clasts yielded the planktonic foraminifera *Helvetoglobotruncana praehelvetica* (fig. 7i), *Whiteinella archaeocretacea* (fig. 7j), *Whiteinella sp.* (Fig. 7k), and badly preserved *Thalmanninella greenhornensis* (Fig. 7l), pointing to a late Cenomanian age (~95-93 Ma) (see B**o**uDagher-Fadel, 2015) for carbonate source rocks. Collectively, these pieces of evidence indicate that the Kcv unit was deposited in the Cenomanian, and was overlain by the Jingzhushan Formation after the Cenomanian (post-95-93 Ma), during the Turonian (around 92 Ma), and before the late Campanian (80 Ma).

4.4 Conglomerate and sandstone petrography

Conglomerate clasts in the Kcv unit are dominantly volcanic (> 95%), with minor sandstone and chert. At the base of the Jingzhushan Formation in section SE-N04a, either volcanic (20-73%) or Langshan limestone clasts (25-79%) are dominant (Fig. 4 e,f). The middle and upper Jingzhushan Formation are characterized by *Orbitolina*-rich limestone clasts (> 84%), associated with sandstone-siltstone (2%–16%), and rare chert.

Twenty-eight sandstone samples from five sections of the Jingzhushan Formation are mostly quartzo-lithic and subordinately litho-quartzose and lithic (average modal composition Q:F:L = 28:2:70; Appendix Table S2; Fig. 8a). Grains are poorly sorted, angular to subrounded, and calcite-cemented. Mainly monocrystalline quartz represents only 1-4% of framework grains at the base of the Jingzhushan Formation in section SE-N04, and increase to 16-25% in the middle and upper members in sections SE-N02, 03 & 05, reaching maximum (28-59%) in section SE-N01. Lithic grains (40-96%) are mainly andesitic-felsic volcanic (43% of total lithic grains on average) and limestone fragments (56% of total lithics); chert, mafic and metamorphic rock fragments are rare.

4.5. Detrital zircon U-Pb ages and Hf isotopes

In the Kcv unit, we obtained 73 valid ages from sample 15DZ35 (section SE-N04, south of Daze Co, Nima area). Among these, 64 cluster between 90 and 120 Ma (peak at 105 Ma), and show εHf(t) values between +7.4 and +14.4 with T^{C}_{DM} model ages between 0.25 and 0.69 Ga (Fig. 10; Appendix Table S4).

In the Jingzhushan Formation, samples 13MD02, 13MD12, and 13MD15 (section SE-N01, Duba area) yielded 194 valid ages, 126 of which between 90 and 150 Ma (peak at ~120 Ma). Seventy-seven Mesozoic zircons yielded εHf(t) values between -24.1 and +7.4, with T^{C}_{DM} model ages between 0.71 and 2.73 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 250-350, 400-650, 700-950, 1000-1200, 1800-1950, and 2250-2600 Ma age ranges (Fig. 9).

Sample 15QGC03 and 15QGC24 (section SE-N02, north of Qiagui Co; Fig. 1b) yielded 145 valid ages, 97 which between 90 and 150 Ma (peaks at 97 and ~120 Ma), Seventy-five Mesozoic zircons yielded εHf(t)values between -16.2 and +15.31, with T^{C}_{DM} model ages between 0.18 and 2.28 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 250-350, 450-500, 700-950, 1000-1250, and 1800-2000 Ma age ranges (Fig. 9).

Out of the 93 valid ages obtained from section SE-N03 (south of Wuru Co), 73% are younger than 250 Ma (Table 2). Forty-eight Mesozoic zircons yielded εHf(t) values between -11.4 and +11.8, with T^{C}_{DM} model ages between 0.40 and 1.89 Ga (Appendix Table S4; Fig. 10). The complex age spectrum includes clusters at 90-120, 250-300, 300-600, 900-1100, and 1850-2050 Ma (Fig. 9).

Sample 15DZ25 (section SE-N04, south of Daze Co, Nima area) yielded 72 valid ages, 42 of which younger than 250 Ma (Fig. 4 E). Thirty Mesozoic zircons yielded εHf(t) values between -18.6 and +14.7, with T^{C}_{DM} model ages between 0.22 and 2.38 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 250-350, 350-500, 750-900, 1050-1150, and 1700-2000 Ma age ranges (Fig. 9).

Sample 13QR01 (section SE-N05, south of Zhaxi Co, Gaize area; Fig. 1b) yielded 66 valid ages, out of which 28 between 90 and 160 Ma. Twenty-six Mesozoic zircons yielded εHf(t) values between -12.0 and +19.4, with T^{C}_{DM} model ages between 0.04 and 2.02 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 250-300, 450-500, 700-1000, 1050-1200, 1250-1350, and 1650-1850 Ma age ranges (Fig. 9).

4.6 Provenance interpretation

In the Kvc unit (section SE-N04), imbricate clasts indicate mostly southward direction of sediment transport (DeCelles et al., 2007a and this study). Age spectra and isotopic signatures of detrital zircons (cluster at 90-120 Ma with peak at ~105 Ma; 88% grains with positive εHf(t) values between 7.4 and 14.8) match those from Lower Cretaceous volcanic rocks in the Bangong-Nujiang suture zone (Liu et al., 2017), indicating provenance from the north.

Sedimentary facies of the Jingzhushan Formation suggest limited transport distance (indicatively < 15 km; Blair and McPherson, 1994) and rapid deposition in alluvial-fan to braided-river systems. Detrital zircons with negative εHf(t) values could not derive from the Gangdese arc in the southern Lhasa terrane, which is characterized by high positive εHf(t) values (Fig. 10; Ji et al., 2009; Zhu et al., 2011b and references therein). The lack of detrital zircons in the 190-220 Ma age range (Fig. 9), characteristic of the southern Qiangtang terrane, and of clasts derived from turbiditic sandstones and ophiolites exposed all along the Bangong-Nujiang suture zone in the north, rule out these two potential northern sources as well.

A southern source is suggested by northward paleocurrents documented by clast imbrication and abundance of *Orbitolina*–bearing clasts with microfacies similar to marine limestones exposed in the central-northern Lhasa block (Fig. 7 & 5b; BouDagher-Fadel et al., 2017). Moreover, detrital zircons yielding ages of 90-150 Ma and widely ranging εHf(t) values, or clustering between 1000 and 1300 Ma, match those from Upper Paleozoic strata (Leier et al., 2007c; Zhu et al., 2011a), Cretaceous igneous rocks, and Duoni Formation of the central-northern Lhasa block (Zhu et al., 2011b; Zhang et al., 2012b; Wang et al., 2014b; Sun et al., 2017) (Fig. 9 & 10). We conclude that, contrary to the underlying Kvc unit, the Jingzhushan Formation was fed from the central-northern Lhasa block in the south, where limestones of the Langshan Formation and volcanic sandstones of the Duoni Formation were exposed to erosion.

Obviously, a 180° change in paleocurrents and quite different characteristics in clasts suggests a quick change in provenance from Kcv unit to Jingzhushan Fomation.

5. DAXIONG FORMATION

5.1 Stratigraphy and Sedimentology

The Daxiong Formation is at least 550 m thick in section SE-S02 (Tangra Yum Co area), whereas only ~45 m thick conglomerates are exposed in section SE-S01 (Nam Co area) (Fig. 3).

Red pebble to cobble conglomerate beds are characterized by lithofacies Gcm and Gch. Sandstone beds, 0.3-0.5 m thick and displaying horizontal planar lamination or trough oblique lamination (Sh and St, Table 1) occur in discontinuous thin interlayers atop coarse conglomerate beds. Unsorted and matrix-supported clasts are subangular to subrounded, and range mostly from 2 to 10 cm in diameter with maximum size over 40 cm.

Red sandstones are well exposed and represent over 450 m of section SE-S02b. In the lower part, fine to medium-grained sandstones show climbing-ripple lamination, horizontal lamination, or trough oblique lamination (lithofacies Sh and St). The upper part is instead characterized by monotonous red and yellow siltstone locally yielding fossil plants (lithofacies Fr); minor sandstone lenses ~50 cm-thick, displaying ripples and horizontal lamination, are intercalated (lithofacies Sh).

5.2 Environmental interpretation

Conglomerates exposed in the Nam Co area compare with the middle conglomerate member 2 of the Daxiong Formation in the Coqen basin (Sun et al., 2015b), indicating deposition in a proximal alluvial fan next to a mountain front (Blair, 1999; Chen et al., 2017). The sandy lithofacies assemblage exposed in the Tangra Yum Co area (lithofacies Sh and St) was deposited in unstable braided-river channels (Miall, 1996)). Monotonous fine-grained sequences in the upper part, comparing with the upper siltstone/mudrock member 4 in the Coqen basin, are interpreted as floodplain deposits with discontinuous lenses of fine sandstone representing crevasse-splay deposits or migrating stream-flow channels (Miall, 1996). The Daxiong Formation was thus deposited in alluvial fans and braided rivers.

5.3 Age constraints

The Daxiong Formation lacks fossils and interbedded tuffs. Its maximum depositional age is constrained by the youngest detrital zircons, dated as 94±2 Ma in the Tangra Yum Co area (16DG08) and as 87±3 in the Nam Co area (15NMC13). Because the unit is unconformably overlain by uppermost Cretaceous-Paleogene Linzizong volcanic rocks (Liu et al., 2004; Pan et al., 2004) and no zircon grain younger than 85 Ma was found, we conclude that the Daxiong Formation was deposited around Turonian-Coniacian times. According to Sun et al. (2015b), in the Coqen basin the unit was deposited between the early Cenomanian (~96 Ma) and the Turonian (~92 Ma at least).

5.4 Conglomerate and sandstone petrography

In section SE-S02 (Tangra Yum Co area), volcanic rocks represent 65% of total clasts, with 7% quartz-rich sandstone, and 28% chert. Similar proportions were observed in the Coqen basin (Sun et al., 2015b). In section SE-S01 (Nam Co area), clasts are mostly volcanic (35-42%), sandstone (15-24%), and metamorphic limestone (35-40%), with minor chert.

Sandstones are poorly sorted with mostly angular to subrounded grains (Fig. 5g, h). Nine samples from two sections are quartzo-lithic (average modal composition Qt:F:L=24:4:72; Appendix Table S2; Fig. 8a). Lithic grains (66 - 85% of the framework) are mainly felsitic and subordinately microlitic volcanic fragments. Quartz (10 - 33%) is mostly monocrystalline and occasionally well rounded.

5.5 Detrital zircon U-Pb ages and Hf isotopes

Zircon grains from sample 15NMC13 (section SE-S01, northwest of Nam Co) yielded 28 out of 75 valid ages in the 90–160 Ma range. Thirty-one zircon grains of Mesozoic age yielded εHf(t) values between -10.4 and +10.5, with T^{C}_{DM} model ages between 0.54 and 1.79 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 500-600, 450-500, 700-1000, 1050-1200, 1300-1400, and 1800-2500 Ma age ranges (Fig. 9).

Zircon-age spectra from samples 16DG02 and 16DG08 (section SE-S02, east of Tangra Yum Co) are similar (Fig. 3). Out of 135 valid ages, 117 cluster between 90 and 140 Ma. Twenty-six zircon grains with Mesozoic age yielded εHf(t) values between -12.6 and +9.1, with T^{C}_{DM} model ages between 0.58 and 1.99 Ga (Appendix Table S4; Fig. 10). Older U-Pb ages cluster in the 450-500 and 1050-1300 Ma age ranges (Fig. 9).

5.6 Provenance interpretation

The lack of detrital zircons yielding ages between 90-160 Ma and εHf(t) values > 10 rule out provenance from the Gangdese arc in the southern Lhasa terrane, and indicates a northern source in the central-northern Lhasa block. The BNSZ and southern Qiangtang terrane have similar zircon age patterns (cluster at ~110 Ma) and εHf(t) values. However, such a source is unlikely, because at Late Cretaceous time the central-northern Lhasa block was elevated and supplied detritus to the Jingzhushan Formation along the northern margin of the Lhasa block adjacent to the BNSZ (DeCelles et al., 2007a and this study). The central-northern Lhasa block is therefore the only plausible sediment source for the Daxiong Formation, specifically including Zelong volcanic rocks exposed in the north, as indicated by southward palaeocurrent directions and abundance of andesitic and felsitic volcanic grains. Clasts of metamorphic limestone and Mesoproterozoic zircons (1000-1300 Ma, peak at ~1150 Ma) with ages matching those from Upper Paleozoic strata of the northern Lhasa terrane (Leier et al., 2007c; Zhu et al., 2011a) suggest additional contributions from underlying Paleozoic strata.

6 DISCUSSION

6.1 The growth of the Northern Lhasaplano

The Jingzhushan Formation, together with the Daxiong Formation in the south (Fig. 11), were initially characterized by middle fan to braidplain environments passing upward to proximal alluvial fans and finally braided rivers. Deposition was rapid, with gravel size and volume increasing first and decreasing next. For both formations, deposited at the same time, provenance analysis suggests supply from the central-northern Lhasa block via north- and south-directed short and steep drainage systems. Therefore, in the early Late Cretaceous the central-northern Lhasa block ceased to be a basin and was rapidly uplifted to become a major source of detritus.

Evidence of tectonic activity at this time include northward motion along the Gaize–Selin Co thrust south of the basin in which the Jingzhushan Formation was being deposited (DeCelles et al., 2007a), and southward motion along the Gugu La thrust along the northern side of the Coqen basin where the Daxiong Formation was being deposited (Murphy et al., 1997). The areal distribution of the Gugu La thrust is the same as that of the Daxiong Formation, both extending eastward to the Nam Co (Pan et al., 2004). Structural restorations document more than 50% crustal shortening across the Lhasa block during the Cretaceous (Murphy et al., 1997; Kapp et al., 2007a, 2007b; Volkmer et al., 2007) (Fig. 11). Moreover, penecontemporaneous Mg-rich and adakitic magmatism in the Lhasa block point to a thickened juvenile lower crust (Ma and Yue, 2010; Yu et al., 2011; Wang et al., 2013, 2014b; Sun et al., 2015a) (Fig. 11).

Sedimentological and provenance analysis concur with tectonic and magmatic evidence to indicate significant early Late Cretaceous growth and erosional exhumation of the central-northern Lhasa block, named the Northern Lhasaplano, topographic remnants of which are still seen in satellite images between the Gangdese arc and the BNSZ (Fig. 1a).

6.2 Timing of initial tectonic uplift

Widespread deposition of Orbitolina-rich Langshan limestones on the northern Lhasa block continued until at least the late Cenomanian and possibly the early Turonian (95-92 Ma). U-Pb zircon dating of tuffs interlayered between the middle and upper member of the Jingzhushan Formation at 92.2±0.8 Ma constrain precisely the timing of conglomerate deposition and the beginning of significant topographic growth and erosion of the Northern Lhasaplano. Evidence from magmatic rocks suggested that the lower crust of the central-northern Lhasa block was thickened and delaminated between 95 and 88 Ma (Ma and Yue, 2010; Yu et al., 2011; Wang et al., 2013, 2014b; Sun et al., 2015a) (Fig. 11). The Gaize–Selin Co and Gugu La thrusts became active at this time as well (Murphy et al., 1997; DeCelles et al., 2007a). Chronostratigraphic, structural, and magmatic evidence thus concur to indicate that topographic growth of the Northern Lhasaplano began at early Turonian times (not much earlier and not later than 92 Ma).

6.3 Extension of the Northern Lhasaplano

Synorogenic conglomerates are useful paleogeographic indicators of fault-bounded uplifts (Van Houten, 1969; DeCelles, 1988; Harrison et al., 1992; Sun et al., 2005; Wang et al., 2010). The long and narrow belts of alluvial-fan conglomerates deposited in the central-northern Lhasa block on the opposite sides of an area lacking Upper Cretaceous-Paleogene strata (XZBGM, 1993) confine the northern and southern margins of the uplifted northern Lhasaplano (Fig. 1b), which is delimited by the northward Gaize–Selin Co thrust in the north and by the southward Gugu La thrust in the south. The northern front of the Northern Lhasaplano was thus over 1000 km long, from Rutog(Li et al., 2014b), across the Zhaxi Co, Daze Co in Nima, Wuru Co, Qiagui Co in Shenzha, Duba in Baingoin, to Biru. Its southern front extended for ~ 700 km from the Coqen basin (Sun et al., 2015b) and across the Tangra Yum Co to west of the Nam Co (Fig. 1b). Presently, the area comprised between the Jingzhushan and Daxiong conglomerate belts is 80-150 km-wide, indicating that the Late Cretaceous Northern Lhasaplano extended in an E-W direction covering an area of 80,000 km^2 at least. Accurate paleo-altimetry studies are still needed to assess the absolute amount of surface uplift.

6.4 Palaeogeographic and tectonic evolution

Upper Jurassic to Lower Cretaceous non-marine strata exposed along the Bangong-Nujiang suture, together with provenance analysis of Lower Cretaceous strata exposed in the northern Lhasa block, suggest that the Bangong-Nujiang suture zone underwent topographic growth and erosion in the Aptian–Cenomanian (Kapp et al., 2005, 2007b). At this time, most of the Lhasa block was occupied by a shallow epicontinental sea dominated by carbonate sedimentation (Fig. 12a; Leier et al., 2007b; Zhang et al., 2004, 2012b; Sun et al., 2017). Topographic growth in parts of central Lhasa began in the earliest Albian (e.g., Damxung area; Wang et al., 2017b), where rapid erosional exhumation started to feed the Xigaze forearc basin at the southern edge of the southern Lhasa block (Wang et al., 2017a).

Rapid deposition of the Jingzhushan and Daxiong alluvial conglomerate belts, documenting seaway retreat and provenance from the central-northern Lhasa block took place at early Turonian time. Magmatic evidence indicate penecontemporaneous crustal thickening to ~50 km beneath the Northern Lhasaplano, delimited by the Gaize–Selin Co and Gugu La thrusts (Figure 12b; Sun et al., 2015a). Significant crustal thickening of the southern Lhasa terrane, instead, did not occur before 70 Ma (Zhu et al., 2017), and detritus from central Lhasa started to feed shelfal sediments of the Xigaze forearc basin around 88 Ma (An et al., 2014). The Lhasa block, therefore, was uplifted in successive steps, first in the north and next in the south. The southern Qiangtang block and the Bangong-Nujiang suture zone were uplifted even earlier than the Northern Lhasaplano, thus defining a topographic wave moving stepwise from north to south across the Lhasa block during the Cretaceous.

7. CONCLUSIONS

The Jingzhushan and Daxiong formations of the central-northern Lhasa block testify to deposition in alluvial-fan and braided-river systems at Turonian-Coniacian times (from about 93 Ma to at least 87 Ma), after rapid transition from shallow-marine environments in the Aptian-Cenomanian (Langshan Formation).

U-Pb ages and in-situ Hf isotope signatures of detrital zircons, conglomerate and sandstone petrography, and paleocurrent data indicate that the Jingzhushan and Daxiong formations were both derived from the central-northern Lhasa block rather than from the Bangong-Nujiang suture zone or Gangdese arc.

Stratigraphic, sedimentological, and provenance analysis, together with broadly coeval activation of the Gaize–Selin Co and Gugu La thrust belts suggesting shortening and crustal thickening, suggest that the actively eroding highlands feeding the Jingzhushan and Daxiong conglomerate-bearing units along its opposite sides had prominent and widespread topographic growth during the early Late Cretaceous， forming what we have named the Northern Lhasaplano.

The age of the youngest marine deposits, of provenance change, and of tectonic shortening is younger in the southern Lhasa terrane than in the northern Lhasa terrane and the Bangong-Nujiang suture zone, indicating earlier surface uplift and retreat of seaways from north to south across the Bangong-Nujiang suture zone and the Lhasa block during Cretaceous time.

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Table 1 Lithofacies found in the measured sections(Miall, 1996; Jo et al., 1997)

Facies code	Description	Interpretation
Gch	Pebble to cobble with few thick of set-packages conglomerate, well sorted and clastic supported, sub-angular to subround, slightly normal grading, horizontally stratified and basal erosive boundary	Deposition under clast-supported debris flows, shallow traction currents, or gravelly low relief bars
Gcm	Pebble to very coarse cobble size conglomerate, clastic supported with a sandy matrix, subround gravel, poorly to moderately sorted, crudely horizontal bedding, weak grading with imbricated clasts, poorly organized with few thick layers and basal erosive boundary	Deposition by clast-rich debris flows or traction currents under relatively rapid accumulated rates
Gmm	Medium Pebble to medium boulder conglomerate, poorly to moderately sorted, angular to subround gravel, massive conglomerate with the mud matrix supported, disorganized and unstratified, normal grading or inverse grading	Deposition by matrix-rich debris flow under the braided river channel
Sp	Medium to very coarse grained sandstone with wedge shaped, moderately-poorly sorted, planar stratification with sandy layers, can be pebbly	Deposition by migration of large dunes under shallow unidirectional flows
Sr	Fine to medium grained and moderately sorted sandstone with small and asymmetric current ripples	Deposition by shallow unidirectional flows regime, migration of ripples
Sh	Fine- to medium-grained sandstone with planeparallel lamination	Upper plane bed conditions under unidirectional flows, either strong (>100 cm/s) or very shallow
St	Medium- to very coarse grained sandstone with trough cross-stratification, can be pebbly	Migration of large 3D ripples (dunes) under moderately powerful (40–100 cm/s), unidirectional flows in large channels
Fl	Reddish mudstone and silty mudstone beds, small current ripples, horizontally-laminated bed	Deposition by flood plain, distal alluvial plain or abandoned channel deposits
Fr	Massive reddish laminated red, green, or gray siltstone beds bounded at the top by erosive surfaces, horizontally laminated, lens or wedge shaped interbedded siltstone and fine sandstone, occasionally carbonate nodules occurred	Deposition of flood plain, distal alluvial plain

Table 2 Summarized characteristics of detrital zircon U-Pb ages of sandstone samples in the Jingzhushan and Daxiong Formation

tion	Sample	Analyzed numbers of zircon grain	Percentage of the Mesozoic ages	Maximum depositional Age (Ma)	YDZ[a]	YSG[b]	YPP[c]	YC1σ(2+)[d]	YC2σ
N01	13MD02	73	51%	90.5 ± 4.2	89 +2.1 -3.7	89 ± 3	89	90.5 ± 4.2 (n=2)	109.3 ± 2
	13MD12	68	82%	98.7 ± 5.0	96.2 +6.4 -9.4	98 ± 5	116	98.7 ± 5.0 (n=2)	104.2 ± 4
	13MD15	62	65%	100.6 ± 3.3	94.3 +5.2 -7.1	94 ± 3	112	100.6 ± 3.3 (n=2)	101.6 ± 2
N02	15QGC24	73	67%	93.0 ± 2.3	87 +5 -6.8	87 ± 3	98	93.0 ± 2.3 (n=3)	94.0 ± 1.
	15QGC03	74	66%	91.5 ± 2.0	89.5 +2.6 -4.1	90 ± 2	98	91.5 ± 2.0 (n=4)	91.5 ± 2.
N03	15MT10	97	73%	91.3 ± 0.8	87.7 +2.1 -5.6	90 ± 2	94	91.3 ± 0.8 (n=19)	92.3 ± 0.6
N04	15DZ25	72	58%	92.4 ± 2.6	85.4 +3.9 -4.8	86 ± 2	93	92.4±2.6(n=6)	92.4 ± 2.
	15DZ35	74	88%	96.0 ± 1.6	87.7 +4.6 -4.3	88 ± 2	100	96.0 ± 1.6 (n=4)	97.6 ± 0.
N05	13QR01	66	42%	90.0 ± 2.7	86.3 +4.4 -7.6	88 ± 3	91	90.0 ± 2.7 (n=4)	90.0 ± 2.
S01	15NMC13	75	45%	87.3 ± 3.3	86.3+3.2 -5.2	87 ± 2	94	87.3 ± 3.3 (n=2)	88.4 ± 2.
S02	16DG02	70	91%	104.8 ± 2.0	102.3 +2.9 -3.5	104±2	117	104.8 ± 2.0 (n=4)	106.1 ± 1
	16DG08	75	71%	94.3 ± 2.2	92.3 +2.9 -7.3	94 ± 2	94	94.3 ± 2.2 (n=4)	94.3 ± 2.

Notes: a. YDZ = age calculated by the "Youngest Detrital Zircon" routine of Isoplot (Ludwig, 2008); b. YSG = youngest single detrital zircon age with 1δ uncertainty; c. YPP = youngest graphical detrital zircon age peak on an age-probability plot or age-distribution curve; d. YC1σ(2+) = weighted mean age (±1σ incorporating both internal analytical error and external systematic error) of youngest cluster of two or more grain ages overlapping in age at 1σ; e. YC2σ(3+) = weighted mean age (±1σ incorporating both internal analytical error and external systematic error) of youngest cluster of three or more grain ages overlapping in age at 2σ (Dickinson and Gehrels, 2009).

FIGURE CAPTIONS

Figure 1. a) Simplified tectonic map of the Tibetan Plateau (modified after (Zhu et al., 2011b) and (Wang et al., 2014a)). b) Sketch geological map of the Lhasa block (modified from Pan et al. (2004) and (Kapp et al., 2003a)). JSSZ, Jinsha suture zone; BNSZ, Bangong‑Nujiang suture zone; SNMZ, Shiquan River‑Nam Tso Mélange Zone; LMF, Luobadui‑Milashan Fault; IYZSZ, Indus‑Yarlung Zangbo Suture Zone; THFT, Tethyan Himalaya Fold-Thrust Belt; MCT, Main Central Thrust; MBT, Main Boundary Thrust; MFT, Main Frontal Thrust; SGAT, Shiquan-Gaize-Anduo Thrust; GST, Gaize-Selin Co thrust (DeCelles et al., 2007a);ET, Emei La thrust (Murphy et al., 1997); GLT, Gugu La thrust (Murphy et al., 1997); GT, Gangdese thrust system (Murphy et al., 1997).

Figure 2. Comparison between Cretaceous strata in the central and northern Lhasa terranes (time scale as in Sun et al., 2015b). Lithological legend as in Fig. 3. Alb, Albian; Cen, Cenomanian; Tur, Turonian; Con., Coniacian; San., Santonian; Cam., Campanian.

Figure 3. Stratigraphic columns of the Jingzhushan (SE-N01-05) and Daxiong formations (SE-S01-02), showing sample locations, gravel composition, and paleocurrent indicators. Mb., member.

Figure 4. Field photographs of the Jingzhushan and Daxiong formations: a) lower and middle members (section SE-N01, Duba); b) middle and upper members separated from the Langshan Formation by the Gaize-Selin Co thrust (SE-N02, Qiagui Co); c) same units and thrust in section SE-N03 (Wuru Co area); d) lower member with alternating conglomerate units with volcanic-dominated (Kcv) and limestone-dominated clasts (Kj) (SE-N04); e) conglomerate (SE-N02); f) imbricate clasts indicating northward paleoflow (SE-N04); g) sandstone with oblique lamination (SE-N01); (h) tuff bed (SE-N03); i) imbricate clasts indicating southward paleoflow (SE-S01); j) conglomerate (SE-N02).

Figure 5. Sandstone petrography. a) quartzo-lithic sandstone (13MD12, section SE-N01); b) quartzo- lithic volcaniclastic sandstone (15QGC23, SE-N02); c) quartzo-lithic carbonaticlastic sandstone (15MT09, SE-N03); d) tuff (15MT08, SE-N03); e) lithic carbonaticlastic sandstone (15DZ31, SE-N04); f) lithic sandstone (13QR01, SE-N05); g) lithic volcaniclastic sandstone (15NMC23, SE-S01); h) quartzo- lithic volcaniclastic sandstone (16DG05, SE-S02). Qz, quartz; Pl, plagioclase; Lv, volcanic lithic; Lc, carbonate lithic.

Figure 6. Relative probability weighted mean ages (upper) and concordia diagrams (bottom) of the

intrusive granite (sample 15BJ14) in the Jingzhushan formation in Duba area and the tuff (sample 15MT08) from the section SE-N03.

Figure 7. Photomicrograph of foraminifer from limestone conglomerates.
a) *Conicorbitolina* sp. A, 15DZ06; (b) *Conicorbitolina* cf. *conica* (D'Archiac), 13MD01; c-e) *Mesorbitolina aperta* (Erman), c) 13MD48C; d) 13MD52A; e) 13MD11; f) *Palorbitolinoides hedini* Cherchi et Schroeder, 13MD48C; g) *Mesorbitolina* cf. *birmanica* (Sahni), 13MD46A; h) *Palorbitolina lenticularis* (Blumenbach), 15DZ03; i) *Helvetoglobotruncana praehelvetica* Trujillo, 15MT02; j) *Whiteinella archaeocretacea* Pessagno, 15MT02; k). *Whiteinella* sp., 15MT02; (l) *Thalmanninella greenhornensis* (Morrow), 15MT02. Scale bars: a,b, g, i = 500μm; c, d, e, f, h = 1000μm; j, k, l = 2000μm.

Figure 8. Petrographic plots. Qm= monocrystalline quartz; F= feldspar; Lt=total lithic grains (Lv= volcanic; Ls= sedimentary; Lm= metamorphic). Parameters after Dickinson and Suczek (1979) and Ingersoll et al. (1984); fields after Garzanti (2016).

Figure 9. Relative U-Pb age probability for detrital zircons from b-e, g) Jingzhushan sandstones (sections SE-N01 to N05), f) Kcv sandstone (section SE-N04), and i-k) Daxiong sandstones (sections SE-S01-02 and Coqen basin; Sun et al., 2015b). Results are compared with a) data from detrital zircons in southern Qiangtang and BNSZ (Kapp et al., 2007b; Pullen et al., 2008; Dong et al., 2011; Fan et al., 2011; Zhu et al., 2011a), igneous zircons in southern Qiangtang and BNSZ (Yang et al., 2011; Zhu et al., 2011b; Li et al., 2014c, 2015a; Liu et al., 2017), h) detrital zircons from central-northern Lhasa (Leier et al., 2007b; Zhu et al., 2011a; Zhang et al., 2012b; Li et al., 2014a), igneous zircons from central-northern Lhasa (Chu et al., 2006; Zhu et al., 2009, 2011b; Wang et al., 2014b; Sun et al., 2015a), and l) igneous zircons from southern Lhasa (Chu et al., 2006; Ji et al., 2009; Zhu et al., 2011b).

Figure 10. Age and Hf isotope signatures of detrital zircons from Jingzhushan sandstones (sections SE-N01 to N05) and Daxiong sandstones (sections SE-S01-02 and Coqen basin, Sun et al., 2015b). Results are compared with data from southern Qiangtang and BNSZ (Yang et al., 2011; Zhu et al., 2011b; Li et al., 2014c, 2015a; Liu et al., 2017), igneous zircons from central-northern Lhasa (Chu et al., 2006; Zhu et al., 2009, 2011b; Wang et al., 2014b; Sun et al., 2015a), detrital zircons from Duoni Formation in northern Lhasa terrane (Lai et al. unpublished), and igneous zircons from southern Lhasa (Chu et al., 2006; Ji et al., 2009; Zhu et al., 2011b).

Figure 11. Simplified map indicating location and formation age of the studied sections, together with estimated N-S tectonic shortening (Murphy et al., 1997; Kapp et al., 2003a, 2007a, 2007b;

Volkmer et al., 2007, 2014) and age of Upper Cretaceous magmatic rocks in central-northern Lhasa block (Ma and Yue, 2010; Yu et al., 2011; Wang et al., 2014b; Li et al., 2015b; Sun et al., 2015a).

Figure 12. Paleogeographic and paleogeomorphological cartoons of the Lhasa block in the Cretaceous (not to scale). a) **Aptian–Cenomanian**: most of the area is occupied by a shallow epicontinental sea dominated by carbonate sedimentation (Zhang et al., 2004, 2012b; Leier et al., 2007b). Tectonic uplift and exhumation affected parts of central Lhasa (e.g., Damxung area; Sun et al., 2017; Wang et al., 2017b). The Xigaze forearc basin along the southern edge of the Lhasa block was being filled by deep-water turbidites (Wang et al., 2017a). b) **Turonian-Coniacian**: rapid uplift of the Northern Lhasaplano triggered erosion and accumulation of alluvial-fan conglomerates along its northern and southern flanks. Lack of significant shortening and conglomerate deposition in southern Lhasa indicates limited uplift of the Gangdese arc. Detritus from central Lhasa was recorded in the Xigaze forearc since 88 Ma (An et al., 2014). BNSZ, Bangong-Nujiang suture zone; GST, Gaize-Selin Co thrust; GLT, Gugu La thrust; IYSZ, Indus-Yarlung Zangbo Suture Zone; SGAT, Shiquanhe-Gaize-Amdo thrust belt.

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