The birth of the Xigaze forearc basin in southern Tibet

Jian-Gang Wang^{1,*}, Xiumian Hu², Eduardo Garzanti³, Wei An⁴ and Xiao-Chi Liu¹

15 **ABSTRACT**

16 The stratigraphic succession of a forearc basin provides crucial information on the
17 history of a convergent plate margin. In particular, it helps to establish the origin of
18 the underlying ophiolites and to unravel the earliest evolutionary stage of arc-trench
19 systems, which remain poorly understood. The Xigaze forearc basin in southern Tibet
20 is one of the best examples of a fossil forearc basin. This study illustrates detailed
21 stratigraphic and high-precision SIMS U–Pb zircon geochronological and Hf isotopic
22 data from the Chongdui Formation, representing the very base of the Xigaze
23 forearc-basin succession, and reconstructs when and how the basin was formed. The
24 Chongdui Formation includes tuffaceous chert and siliceous mudrocks deposited
25 directly on top of pillow basalts of the Xigaze ophiolite and conformably overlain by
26 volcaniclastic turbidites. Tuff layers are interbedded throughout the unit, and their
27 U–Pb zircon ages range from 119 to 113 Ma in the lower member and from 113 to
28 110 Ma in the upper member, broadly consistent with the established radiolarian
29 biostratigraphy. U–Pb ages and Hf isotope signatures of zircons contained in both tuff
30 layers and turbiditic sandstones indicate clear affinity with magmatic rocks of the
31 Lhasa terrane. Direct depositional and chronostratigraphic relationship with the
32 underlying oceanic crust, dated between 131 and 124 Ma, proves that the Xigaze
33 ophiolite is the basement of the Xigaze forearc basin. After an initial prolonged stage
34 of starved siliceous sedimentation, influx of terrigenous detritus began at 113–110 Ma,
35 reflecting the onset of topographic growth and erosion of the Lhasa terrane in
36 response to intense magmatic activity. Formation of the ophiolitic basement during the
37 early stage of subduction and the subsequent topographic growth of the arc source
38 induced by subduction-related magmatism are thus two critical factors for the birth of
39 the Xigaze forearc basin. Similar stratigraphies were identified in the Great Valley and

Luzon Central Valley forearc basins, suggesting that the initial geodynamic evolution of the Xigaze forearc basin may be common to many other forearc basins worldwide.

Keywords: Xigaze forearc basin; chronostratigraphy; provenance; subduction initiation; Tibet.

1. Introduction

Forearc basins develop at convergent plate margins, and are filled principally by volcano-plutonic detritus derived from the adjacent magmatic arc ([Marsaglia and Ingersoll, 1992](#)). Forearc-basin successions generally undergo limited metamorphism, thereby preserving full information on the evolution of the arc-trench system ([Dickinson, 1995](#)). Over the past decades, numerous studies have contributed to our understanding of the sedimentary evolution of forearc basins in close relationship with subduction-related tectono-magmatic events (e.g., [Ingersoll, 1979](#); [Dürr, 1996](#); [Wu et al., 2010](#); [An et al., 2014](#); [Orme et al., 2015](#); [Orme and Laskowski, 2016](#)). However, the origin and early development of forearc basins, the reconstruction of which is essential to unravel the dynamics of subduction initiation, the supra-subduction origin of ophiolites and the counterintuitive role of overriding plate extension, are still poorly understood (e.g., [Hopson et al., 2008](#)). This is chiefly because the forearc basement is generally concealed beneath a several-kilometer-thick basin fill or is deformed and detached tectonically from the overlying stratigraphic sequence, and/or exposed discontinuously after incorporation in the orogenic belt.

The Xigaze forearc basin (XFB) in southern Tibet formed during northward subduction of the Neotethyan oceanic slab and was filled by a thick sedimentary succession passing upward from upper Aptian to Santonian deep-marine turbidites (Chongdui and Ngamring formations) to Campanian-Maastrichtian shelfal and fluvio-deltaic sediments (Padana and Qubeiya formations) (Wang et al., 2012; An et al., 2014). In the western part of the XFB, sedimentation was continuous until the early Eocene, as documented by Paleocene–Eocene carbonates and clastic fluvial sediments (Quxia and Jialazi formation) (Orme et al., 2015; Hu et al., 2016). Owing to its complete and well-exposed stratigraphy, the XFB is one of the best examples of a fossil forearc basin, and particularly well suited to study the tectonic, erosional and sedimentary evolution of the Transhimalayan arc-trench system (e.g., Wang et al., 2012; An et al., 2014; Orme et al., 2015; Orme and Laskowski, 2016).

The aim of the present article is to clarify the origin of the XFB and to reconstruct in detail its earliest evolutionary stage, by focusing on the stratigraphic base of the XFB represented by the Chongdui Formation. Several studies have suggested that the XFB was built above the Xigaze ophiolites (Nicolas et al., 1981; An et al., 2014; Orme and Laskowski, 2016). However, a controversial alternative scenario was postulated by Aitchison et al. (2000), who suggested that the ophiolite as well as the underlying Chongdui Formation were formed in an intra-oceanic-arc setting far off the southern margin of Asia, and recorded an independent forearc system unrelated to the XFB. Based on accurate stratigraphic, geochronological and isotopic data, this article provides firm constraints on the depositional timing and

tectonic setting of the Chongdui Formation, and discusses briefly the implications for the origin of forearc basins worldwide.

2. Geological background

The XFB in southern Tibet is part of the arc-trench system associated with the northward subduction of Neotethyan lithosphere, which ended in the middle Paleocene when the Indian and Asian continental margins started to collide (Hu et al., 2015). Tectonically, the XFB lies between the subduction-related magmatic arc on the Lhasa terrane to the north and the Yarlung-Zangbo ophiolitic suture zone to the south (Fig. 1). Magmatic rocks in the Lhasa terrane comprise dominantly upper Mesozoic to Paleogene granitic intrusions and related volcanic products, which delineate two belts with distinct magma sources (Chu et al., 2006; Zhu et al., 2011). The Gangdese magmatic belt yields predominantly zircons with positive $\epsilon_{\text{Hf}}(t)$, indicating a juvenile source (e.g., Ji et al., 2009), whereas the central Lhasa magmatic belt is characterized by zircons with negative $\epsilon_{\text{Hf}}(t)$, indicating re-melting of older crust (e.g., Chiu et al., 2009). The sedimentary cover in the Gangdese belt is limited and mainly Jurassic–Cretaceous in age. By contrast, it is widespread in the central Lhasa belt, including Permian–Carboniferous metasediments and Upper Jurassic–Lower Cretaceous carbonates and volcanoclastics (e.g., Leier et al., 2007a, b). The Yarlung-Zangbo suture zone south of the XFB, representing the tectonic boundary between India and Asia, includes the Yarlung-Zangbo ophiolites (termed as the Xigaze ophiolite in the Xigaze region), the subduction-related mélangé, and post-collisional conglomerates (e.g., Hébert et al., 2012; An et al., 2017; Wang et al., 2013). Further to

the south lies the Tethys Himalayan sedimentary succession, originally deposited along the northern passive margin of India (e.g., [Sciunnach and Garzanti, 2012](#)) ([Fig. 1](#)).

3. Stratigraphy and sedimentology

The strata of the XFB form an asymmetric synclinorium striking W–E ([Einsele et al., 1994](#)). The Chongdui Formation, representing the stratigraphic base of the XFB, is well exposed along the southern edge of the basin. Four continuous sections of the Chongdui Formation distributed for ~110 km along strike were measured ([Fig. 1](#)). The stratigraphy and sedimentary facies of the measured sections are illustrated below.

3.1 The Qunrang-1 section

Description. The Qunrang-1 section (29°09'17.7N", 89°02'40.2"E), which is the type section of the Chongdui Formation, crops out on the hillside above Qunrang village. It consists of ~95 m thick, steeply north-dipping strata resting stratigraphically on top of pillow basalts of the Xigaze ophiolite ([Fig. 3A](#)). Two lithostratigraphic units are identified: a lower member comprising purplish red chert (6.4 m thick) overlain by siliceous mudrocks (12.6 m thick), and a conformably overlying upper member dominated by sandstones and shales (76 m thick) ([Fig. 2](#)). The top of the succession is faulted against a different sliver of ophiolitic basalt to the north.

Chert beds in the lower member are commonly 5–10 cm thick and rich in radiolarian fossils ([Figs. 3B and 4A](#)), whereas siliceous mudrocks are massive. Tuffaceous laminae and thin tuff layers (0.5–3 cm) are common throughout the lower

member (Figs. 2 and 4B), increasing in frequency and thickness (up to 10 cm) up-section (Figs. 3B and C). The upper member comprises thin-bedded, fine-grained sandstones, greenish gray shales, minor purplish radiolarian mudrocks, and medium to thick-bedded (10–60 cm) white tuffs (Fig. 3E). Sandstone beds, commonly 5–20 cm thick, laterally continuous (Figs. 3C and E) and arranged in thickening-upward cycles (Fig. 2), include massive, plane-parallel-laminated and rippled sandstones (Fig. 3D). Four lenticular conglomerate beds with siliceous matrix are intercalated in the siliceous mudrocks of the lower member (Fig. 3C), and two conglomerate beds with sandy-mud matrix occur in the upper member. Conglomerate clasts are mostly subangular to angular basalt and minor diabase, gabbro and serpentinite.

Facies interpretation. Radiolarian chert and interbedded tuffs represent abyssal sediments deposited onto oceanic crust with intercalated fallout tephra. Tuffaceous material increased during deposition of the overlying siliceous mudrocks. Sandstones of the upper member were deposited by low-density turbiditic flows on a lower fan (Mutti, 1992; Einsele et al., 1994; Dürr, 1996), whereas the conglomerates with mafic and ultramafic gravel were deposited by submarine debris flows sourced from nearby ophiolitic highs.

3.2 The Qunrang-2 section

Description. The Qunrang-2 section (29°08'46.9"N, 89°01'42.6"E) lies ~ 2 km SW of the Qunrang-1 section and has similar lithofacies. Strata rest stratigraphically on pillow basalts of the Xigaze ophiolite. Interlayered purplish red chert in mainly 10–15 cm thick beds and massive basaltic breccia at the base (~ 20 m thick, Fig. 3F)

are overlain by purplish red siliceous mudrocks (~ 30 m thick), followed in turn by interlayered sandstones and greenish gray or purplish red mudrocks (>100 m thick) (Fig. 2). Strata in the upper part of the section are intensely deformed and folded under a north-directed thrust with ultramafic rocks in the hanging wall.

Sandstones increase upward in frequency, bed thickness and grain size. In the lower part they are mainly fine-grained, 2–5 cm thick, and may display plane-parallel lamination, whereas in the upper part they are commonly medium- to coarse-grained and mainly 5–20 cm but even 50 cm thick. Three lenticular, clast-supported conglomerate beds with rounded to subrounded volcanic pebbles occur in the uppermost part of the section. Very thin (<5 mm) tuffaceous layers are frequently observed throughout the section; a 1.2 m thick tuff layer occurs at the top.

Facies interpretation. Chert and siliceous mudrocks document deposition in an abyssal plain periodically interrupted by fallout tephra. Thin bedded, fine-grained sandstones were deposited by low-density turbiditic flows in a distal submarine-fan environment (Orme and Laskowski, 2016). Thicker and coarser sandstones and conglomerates suggest deposition by high-density turbiditic flows in a channelized middle fan (Talling et al., 2012).

3.3 The Naxia section

Description. The Naxia section (29°08'14.0N", 89°26'30.3"E), exposed ~60 km west of the Qunrang-1 section, crops out on a hill slope south of Naxia village (Fig. 1). The ~135 m succession stratigraphically overlies pillow basalts (Figs. 2 and 3G). The lower part (~70 m thick) consists of greenish-gray to purplish-red siliceous mudrocks

with thin (1–5 cm) tuffaceous chert and felsic tuffs (Figs. 3H and I). Tuff layers thicken upward to 10–20 cm at the top. The upper part (~65 m thick) is characterized by up to thick (50–100 cm) beds of medium- to very-coarse grained and poorly sorted sandstones or massive matrix-supported conglomerates (Fig. 3J). Sandstone beds may show plane-parallel-lamination and commonly have erosional base. Conglomerate beds are 1–4 meters thick, laterally continuous for tens of meters only, and contain pebbles to boulders of sandstone, shale, chert, limestone and volcanic rocks. Thin-bedded, fine- to medium-grained sandstones and greenish shales are intercalated with thick bedded sandstone and conglomerates, which commonly display plane-parallel-lamination and climbing ripples. The top of the Chongdui Formation is covered at the foot of a hill.

Facies interpretation. Abyssal deposition of siliceous mudrocks and tuffaceous chert pass upward to sedimentation of coarser and thick bedded sandstones by high-density turbiditic flows, interpreted as channel deposits in a middle to inner fan (Einsele et al., 1994). Thin bedded sandstones with parallel lamination and climbing ripples represent channel-levee deposits (Talling et al., 2012). Massive conglomerates containing both allochthonous limestone blocks and intraformational sandstone and chert clasts are interpreted as submarine debris flows or slump deposits (Orme and Laskowski, 2016).

3.4 The Polio section

Description. The Polio section (29°17'31.8"N, 89°26'27.7"E), ~50 km NE of the Qunrang-1 section, crops out on a hill slope east of Polio village (Fig. 1). The lower

28 m consist of medium bedded (15–30 cm thick), dark gray tuffaceous chert overlying pillow basalt (Fig. 3K), passing upward to thinner (5–10 cm) pale gray beds intercalated with yellowish siliceous mudrocks up-section. A ~2 m-thick basalt layer also occurs (Fig. 2). This lower chert member is conformably overlain by an upper member consisting of dark shales and sandstones (Fig. 3L). Sandstones occur in mostly thin (2–5 cm), very fine-grained tabular beds locally showing plane-parallel-lamination to climbing ripples or in thicker (15–25 cm), fine- to medium grained lenticular beds. Very thin (< 5 mm thick) tuffaceous layers are common. The contact with overlying strata is not exposed.

Facies interpretation. Abyssal chert sedimentation shows increasing influence of tuffaceous fallout. Lenticular sandstones were deposited in shallow, unstable channels within the lower fan, whereas thin bedded, tabular sandstones document sedimentation in channel levee to interchannel regions (Mutti 1992; Einsele et al., 1994).

Stratigraphic observations in all four sections prove that the Chongdui Formation was deposited stratigraphically onto pillow basalts of the Xigaze ophiolite. The succession comprises a lower member of tuffaceous chert and siliceous mudrocks and an upper member of turbiditic sandstones (Fig. 2). Tuffaceous layers are common throughout the succession, and generally become thicker up-section (Fig. 3B). Lenticular conglomerates with clasts derived from the ophiolitic basement and its cover strata were occasionally deposited by submarine debris flows sourced from adjacent topographic highs. Turbiditic sandstones consist of andesitic to felsitic

volcanic rock fragments and plagioclase, with minor monocrystalline quartz and serpentinite grains (Figs. 4C–F). Accessory minerals include biotite, pyroxene, epidote, spinel, and zircon.

4. Analytical methods

In order to constrain precisely the depositional age of strata and to trace their volcanic sources, thirteen tuffs and six sandstones were collected (sample positions shown in Fig. 2) for *in situ* zircon U–Pb dating and Hf isotope analyses. Zircon grains were handpicked randomly, mounted in epoxy resin and polished to produce a smooth, flat surface. Cathodoluminescence (CL) images were obtained to reveal the internal structure of zircon crystals. All analyses were conducted at the State Key Laboratory of Lithosphere Evolution, Institute of Geology of Geophysics, Chinese Academy of Sciences. The analytical results are given in appendix tables DR1, DR2 and DR3.

Zircon crystals from tuffs were dated using a Cameca IMS-1280HR Secondary Ion Mass Spectrometry (SIMS). The instrument characteristics and analytical procedure are described in Li et al. (2009). The primary O^{2-} ion beam spot is about 20*30 μm in size. Positive secondary ions were extracted with a 10 kV potential. In the secondary ion beam optics, a 60 eV energy window was used, together with a mass resolution of ca. 5400 at 10% peak height, to separate Pb^+ peaks from isobaric interferences. Analyses of the standard Plešovice zircon were interspersed with unknown grains. Pb/U calibration was performed relative to the standard Plešovice zircon ($^{206}Pb/^{238}U$ age 337 Ma); U and Th concentrations were calibrated against

zircon standard 91500. A long-term uncertainty of 1.5% (1s RSD) for $^{206}\text{Pb}/^{238}\text{U}$ measurements of the standard zircons was propagated to the unknowns. Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb . To monitor the external uncertainties of SIMS U–Pb zircon dating calibrated against the Plešovice standard, an in-house zircon standard Qinghu was alternately analyzed as an unknown together with other unknown zircons. Twenty-two measurements on Qinghu zircon yield a Concordia age of 160 ± 1 Ma, which is identical within error with the recommended value of 159.5 ± 0.2 Ma (Li et al., 2013).

Detrital zircons were dated by Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA–ICP–MS). Details of instrumental conditions and data acquisition are illustrated in Xie et al. (2008). A spot diameter of 44 μm was used during the analysis. The raw count rates for ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th and ^{238}U were collected for age determination. The $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios were calculated using the GLITTER program (GEMOC, Macquarie University).

Hf isotope measurements were performed using a Neptune Multi-Collector ICP–MS equipped with the Geolas 193 laser-ablation system. Details on instrumental conditions and data acquisition are illustrated in Wu et al. (2006). Hf isotope analyses were performed with a spot diameter of 60 μm , overlapping on the dated spots within the zircon crystals. During analysis, the obtained average $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of standard zircons GJ-1 and Mud Tank was 0.282019 ± 28 (2SD) and 0.282505 ± 24 (2SD), consistently with previously reported values (Morel et al., 2008; Woodhead and Hergt, 2005).

5. Geochronologic and isotopic results

5.1 SIMS U–Pb ages and Hf isotopes of zircon crystals from tuffs

In the Qunrang-1 section, two samples from the chert unit of the lower member (1.2 m and 5.2 m above the stratigraphic base) were dated as 118.8 ± 1.1 Ma and 116.8 ± 1.7 Ma. Two other samples from the siliceous mudrock unit (12.4 m and 15.8 m above the base) were dated as 113.7 ± 1.4 Ma and 114.3 ± 1.0 Ma. Six nearly equidistant samples from the upper member yielded upward-younging ages decreasing regularly from 113.2 ± 1.5 Ma to 110.8 ± 0.9 Ma. One sample from the top of the Qunrang-2 section yielded an age of 112.1 ± 1.0 Ma. Two samples in the lower ~46 m of the Naxia section were dated as 112.1 ± 0.9 Ma and 110.4 ± 0.9 Ma (Figs. 2 and DR1).

Two groups are defined by Hf isotopic data: one is characterized by positive $\varepsilon_{\text{Hf}}(t)$ values ranging from +5 to +16, and the other by negative to slight positive $\varepsilon_{\text{Hf}}(t)$ values from -15 to +2 (Fig. 5A). Zircons from both groups commonly occur in most samples. Dai et al. (2015) reported Hf isotope data on several zircon grains from a tuff layer in the Qunrang-1 section that are consistent with our results.

5.2 LA-ICP-MS U–Pb ages and Hf isotopes of detrital zircons from turbiditic sandstones

Detrital zircons from all samples show similar age patterns, with mostly Early Cretaceous ages with a notable peak at 112–110 Ma (Figs. 6 A and C). One zircon in sandstone sample 15NX02 yielded a Jurassic age (180 ± 4 Ma), and another from

sample 15QR96 yielded 2503 ± 38 Ma. Eight pre-Cretaceous ages were obtained from sample 15PL28, ranging in age range between 175 Ma and 1483 Ma (Table DR2).

Most zircon grains with Early Cretaceous ages yielded positive $\epsilon_{\text{Hf}}(t)$ values ranging from +10 to +16. A few zircon grains with negative to slight positive $\epsilon_{\text{Hf}}(t)$ values (-7 to +4) occur (Figs. 6 B and D).

6. Discussion

6.1 Stratigraphic age of the Chongdui Formation

The highly precise zircon SIMS U–Pb ages of tuffs, combined with radiolarian faunas studied by Ziabrev et al. (2003), allow an accurate assessment of the depositional age of the Chongdui Formation in different sections. The oldest tuff layer found ~1.2 m above the base of the Qunrang-1 section yielded an age of 118.8 ± 1.1 Ma, consistent with the radiolarian assemblage assigned to the late Barremian (*H. asseni* Zone, Unitary Association 1 of O’Dogherty, 1994). The same radiolarian assemblage was documented at the base of the Polio section (Ziabrev et al. 2003). In the Qunrang-2 section, radiolaria from the base of the siliceous-mudrock unit were assigned to the *T. costata* Subzone (late Early Aptian), comparable to those found in the siliceous mudrocks in the Qunrang-1 section (Ziabrev et al. 2003). Age constraints for the underlying chert unit are lacking. The base of the Naxia section was constrained by the age of the tuff layer to be 112.1 ± 0.9 Ma, at least 6 Ma younger than the base of other sections. Overall, the base of the Chongdui Formation is diachronous, varying in different sections from late Barremian (~123 Ma; Ziabrev et

al. 2003) to latest Aptian (~112 Ma) (Fig. 7).

The onset of turbiditic sedimentation is dated as ~113 Ma in the Qunrang-1 section, as ~112 Ma in the Qunrang-2 section, and as ~110 Ma in the Naxia section (Fig. 2). Further west in the Lazi area (~ 50 km west of the Naxia section), the onset of clastic forearc deposition was dated by U–Pb zircon age of a tuff layer as 110.1 ± 1.3 Ma (Orme and Laskowski, 2016). Overall, data indicate slightly diachronous onset of turbiditic deposition along the forearc-basin strike, being younger in the west (Orme and Laskowski, 2016). Geochronological results are broadly consistent with radiolarian biostratigraphic data, which suggested a late Aptian age for the top of the chert and siliceous mudrock member (*T. costata* Subzone, UA8; Ziabrev et al. 2003) (Fig. 7).

6.2 Provenance and tectonic setting of the Chongdui Formation

Tuff layers yielded two distinct groups of zircons, one with positive $\varepsilon_{\text{Hf}}(t)$ values and the other characterized by negative to slight positive $\varepsilon_{\text{Hf}}(t)$ (Fig. 5A). These two groups compare well to igneous zircons in the Gangdese and central Lhasa magmatic belts (e.g., Chu et al., 2006; Chiu et al., 2009; Ji et al., 2009; Zhu et al., 2011; Hou et al., 2015), respectively (Fig. 5B). Active volcanism during the Early Cretaceous in the Lhasa terrane is thus indicated as the source of the tuffs. Coexistence in the same sample of zircons from both Gangdese and central Lhasa indicates mixing of coeval tuffs from the two belts during fluvial to submarine sediment transport, and/or reworking of penecontemporaneous volcanic materials.

The dominantly late Aptian–early Albian ages of detrital zircons from turbiditic sandstones (with peak at 112–110 Ma, [Fig. 6](#)) are approximate to the depositional age of the turbidites established by zircon SIMS U–Pb dating of tuffs and radiolarian biostratigraphy ([Fig. 7](#)), indicating predominant input from penecontemporaneous volcanic products. Detrital zircons yielded mostly positive $\epsilon_{\text{Hf}}(t)$ values, indicating dominant Gangdese provenance; only a few grains with negative $\epsilon_{\text{Hf}}(t)$ values are interpreted to be derived from central Lhasa ([Fig. 6](#)). Conversely, zircons in tuff layers are derived mainly from central Lhasa, a contrast ascribed to the more explosive character of eruptions in the central Lhasa belt. This interpretation is supported by the spatial distribution of igneous rocks in the Lhasa terrane which indicates intense magmatic activity in the central-northern Lhasa terrane in the Aptian-early Albian time (~120–110 Ma) ([Zhu et al., 2011](#); [Hou et al., 2015](#)). The pre-Cretaceous zircon grains are interpreted as derived from older rocks, or recycled from siliciclastic cover strata in the central Lhasa terrane (e.g., [Leier et al., 2007b](#)).

Presence of detritus from the central-northern Lhasa terrane in the XFB was proposed previously based on heavy minerals (rutile and chromite grains) sandstone petrography (e.g., quartz grains) and old detrital-zircon ages (Paleozoic–Proterozoic) ([Einsele et al., 1994](#); [Dürr, 1996](#); [An et al., 2014](#); [Orme and Laskowski, 2016](#)). Our provenance results are consistent with these studies and indicate that a trans-Gangdese drainage system might have existed since as early as early Albian time, as proposed by [Orme and Laskowski \(2016\)](#).

The presence of zircons with pre-Cretaceous ages and negative $\epsilon_{\text{Hf}}(t)$ values in

the Chongdui Formation points conclusively to provenance from the Lhasa terrane, ruling out the possibility of deposition in an intra-oceanic forearc (Aitchison et al., 2000). A trench-slope-basin setting suggested previously (Yin et al., 1988) is also excluded because the strata are only mildly deformed and were deposited behind and north of the accretionary mélange (An et al., 2017) rather than on top of it (Fig. 1). The stratigraphic relationships and provenance results indicate that the Chongdui Formation was deposited in the Gangdese forearc at the base of the Xigaze forearc-basin succession.

6.3 *Origin of the ophiolitic basement*

The Xigaze ophiolites have been interpreted variously as formed at a slow-spreading mid-ocean ridge (Nicolas et al., 1981), in the back-arc or forearc of an intra-oceanic arc-trench system (Aitchison et al., 2000; Hébert et al., 2012), or in the Gangdese forearc following the onset of subduction (Dai et al., 2013; An et al., 2014; Maffione et al., 2015; Huang et al., 2015). Our stratigraphic and geochronological data demonstrate that the oceanic crust was overlain, soon after its magmatic emplacement (~131–124 Ma, data summarized in Liu et al., 2016), by chert and siliceous mudrocks of the lower Chongdui Formation, containing volcanic material derived from the Lhasa terrane (Fig. 7). The ophiolites, exposed north of the mélange zone documenting the Neotethyan subduction channel (e.g., An et al., 2017) (Fig. 1), were thus formed adjacent to the Lhasa terrane, in the Gangdese forearc (e.g., Dai et al., 2013; An et al., 2014).

Maffione et al. (2015) interpreted the direct contact between the XFB sandstones

and the serpentinized peridotites in the Sangsang and Qunrang (Xigaze region) areas as an unconformity, and suggested that the turbidites overlying the peridotites were deposited immediately after the formation of the ophiolites. Paleolatitudes obtained from the sandstones above the serpentinites in the Sangsang section are indistinguishable from paleolatitude estimates for the Gangdese arc, which were therefore proposed as paleomagnetic evidence for the Gangdese forearc origin of the Xigaze ophiolites (Huang et al., 2015). Because such interpretation is crucial for our understanding of the origin of the XFB and its ophiolitic basement, we have re-examined the contact relationship during the last field season. We could thus observe that the contacts between the serpentinites and the XFB strata in both areas are everywhere in fault contact. In the Sangsang section, the XFB strata overthrust the serpentinized peridotites by a north-dipping fault (Fig. DR2A). Serpentinites near the fault are intensely sheared (Maffione et al., 2015), with fault gouge observed at the top (Fig. DR2C). Strata above the serpentinites consist of medium- to thick-bedded sandstones and dark shales, passing up-section to greenish to red mudrocks and thick bedded sandstones (Fig. DR2B). Similar strata have been studied in detail in the Padana section nearby (~11 km to the east) and correlated to the Padana Formation deposited in pro-delta to delta plain environments during the final stage of XFB evolution (An et al., 2014). Detrital zircon samples from these strata yielded robust depositional age of ~80 Ma, confirming deposition during the late filling stage of the XFB (An et al., 2014), and therefore these strata by no means represent the stratigraphic base of the XFB. In the Qunrang section, the forearc basin turbidites lie

beneath a steep south-dipping thrust with the serpentinized peridotites and sheeted sills in the hanging wall (Fig. DR3A). Slickensides and a brecciated zone were observed in the fault, and rodingite dykes in the fault zone are strongly fractured (Figs. DR3B and C). These observations preclude a depositional contact between the forearc turbidites and the serpentinized peridotites. Exhumation of mantle rocks to the seafloor during forearc hyperextension (Maffione et al., 2015) is thus still unproven.

6.4 Geodynamic control on turbidite deposition

Zircon chronostratigraphy and radiolarian biostratigraphy indicate that deposition of Chongdui Formation turbidites began throughout the basin between 113 and 110 Ma (Fig. 7; section 6.1). The slight age diachroneity along strike may reflect intra-basin topography (Orme and Laskowski, 2016) or diachronous uplift and erosion in the source region (Wang et al., submitted for publication). Timing of deposition onset of turbidites in the XFB is coeval with initial topographic growth on the Lhasa terrane (e.g., Leier et al., 2007a; Orme and Laskowski, 2016). In the Linzhou basin of the southern Lhasa terrane, Lower Cretaceous shallow-marine carbonates (Penbo Member of the Takena Formation) were replaced by fluvial volcanoclastic sediments (Lhunzhub Member of the Takena Formation) indicating initial topographic growth of the Gangdese arc (Leier et al., 2007a). The timing of this transition was constrained by orbitolinid assemblages in the Penbo Member (Boudagher-Fadel et al., 2017) and youngest detrital-zircon ages from the base of the Lhunzhub Member (Leier et al., 2007b) to be late Aptian to early Albian. In the Damxung area of the central Lhasa terrane, fan-delta conglomerates with limestone beds at the base was dated by U–Pb

age of zircons from intercalated tuff layers as ca. 111 Ma (Wang et al., submitted for publication). Topographic growth and erosion of the Lhasa terrane began at the same time as clastic deposition in the XFB, and may have thus caused the sudden influx of volcanic detritus in the XFB.

Two geodynamic processes may have contributed to late Aptian–early Albian topographic growth of the Lhasa terrane: crustal shortening and thickening induced by the Lhasa-Qiangtang collision (Murphy et al., 1997) and/or tectonic and thermal uplift induced by Neotethyan subduction and arc magmatism (Kapp et al., 2007; Leier et al., 2007a). Our provenance data on turbiditic sandstones in the Chongdui Formation indicate that volcanic detritus was derived dominantly from the Gangdese magmatic belt. The lack of metamorphic and sedimentary detritus characteristic of provenance from a collisional orogen suggests a limited influence of the Lhasa-Qiangtang collision. Conversely, the occurrence of numerous tuffs and overwhelming volcanic detritus (Figs. 4C–F) and zircons with ages close to the depositional age (Fig. 6) indicates that contemporaneous magmatism played a fundamental role in the morphological evolution of the source region. Therefore, we conclude that igneous activity subsequent to the initial subduction of Neotethyan lithosphere triggered the topographic growth of the Gangdese arc, eventually leading to erosion and massive sediment supply to the XFB.

6.5 Model for the birth of the Xigaze forearc basin

Newly obtained stratigraphic and geochronological data allow us to reconstruct the earliest history of the XFB in full detail (Fig. 8).

After the Xigaze ophiolite was formed in the Gangdese forearc during ca. 131–124 Ma (Figs. 7), topographic depressions on the newly formed ophiolitic crust were filled by purple chert deposited below the carbonate compensation depth, followed by siliceous mudrocks deposited around the silica compensation depth during late Barremian to late Aptian times (~123–113 Ma) (Fig. 8A). These sediments rest directly on the pillow basalts of the Xigaze ophiolite, which thus represents the basement of the XFB (Fig. 2). A rough forearc-basin substratum with considerable local submarine relief is indicated by the diachronous deposition of the stratigraphic base of the Chongdui Formation (Fig. 7), as well as by the occurrence of channelized gravity-flow deposits containing clasts of various size derived from the entire section of the oceanic lithosphere (Figs. 3C–D).

The lower member of the Chongdui Formation, deposited at very low accumulation rate (19 m in a ca. 10 Ma-long interval in the Qunrang-1 section), documents the very first stage of starved forearc-basin sedimentation, lasting for ~10–15 My (Fig. 7). Contemporaneously to siliceous deposition of the Chongdui Formation, the Sangzugang and Penbo limestones developed in shallow-marine environments along the Gangdese belt (An et al., 2014; Leier et al., 2007a), and the Langshan limestones were deposited in the central-northern Lhasa domain (Boudager-Fadel et al., 2017). These units document minor volcanic supply from the Gangdese arc, and indicate submarine conditions and low relief in most of the Lhasa terrane at that time (Fig. 8A).

The upper member of the Chongdui Formation marks the first arrival of

Gangdese arc-derived turbidites in the forearc basin, which is constrained at 113–110 Ma (Figs. 7). Deposition onset of XFB submarine turbidites reflected the initial topographic growth on the trans-Himalayan arc (Fig. 8B), induced by ongoing subduction of Neothetian lithosphere and related igneous activity (e.g., Kapp et al., 2007; Leier et al., 2007a). Arc magmatism led to continuous topographic growth, erosion and massive sediment supply to the XFB, as recorded by the upper member of the Chongdui Formation followed stratigraphically by the thick turbidites of the Ngamring Formation (Wu et al., 2010; An et al., 2014; Orme et al., 2015; Orme and Laskowski, 2016).

Our study indicates two stages in the early development of the XFB (Fig. 8): a starved earliest stage characterized by very slow deposition of siliceous sediments, followed by much faster accumulation of turbidites. The earliest stage documents a rough depositional surface on top of pillow basalts shortly after the formation of the Xigaze ophiolites, whereas the following stage was controlled by the uplift and erosion on the Gangdese arc resulting from full-regime subduction and igneous activity.

Our reconstruction of the birth of the XFB may have general implications. In the Great Valley forearc basin in California (USA), basal strata are represented by volcano-pelagic sediments including tuffaceous chert, mudrocks and tuffs deposited above the Coast Range ophiolites (161–168 Ma) (e.g., Hopson et al., 2008). After this starved stage of deposition lasted between ~11 and 16 Ma, filling by the Great Valley Group turbidites began in the Late Jurassic–the earliest Cretaceous time (~150–144

Ma) (Dickinson, 1995; Hopson et al., 2008; Surpless et al., 2006). In the Luzon Central Valley forearc basin of the Philippines, upper Eocene pelagic limestones with thin ash layers cap the basalts of the newly formed Zambales ophiolite (~44 Ma; Encarnación et al., 1993). The starved stage lasted for about 10–14 Ma until deposition of volcanoclastic turbidites began in the middle to late Oligocene (Schweller et al., 1984). The similarity of basal sedimentary sequence of forearc basins, comprising a pelagic lower unit representing ~10–15 Ma and deposited on top of the ophiolitic basement and a volcanoclastic upper unit derived from the nearby magmatic arc, suggests that the geodynamic evolution leading to the birth of the XFB may be typical of forearc basins around the world.

Conclusions

This study illustrates in detail the generation and earliest filling stage of the Xigaze forearc basin in south Tibet. Direct stratigraphic evidence and high-precision zircon-dating of tuffs and turbidites from the very base of the Xigaze forearc basin indicates deposition on top of the Xigaze ophiolite, which thus represents the basement of the Gangdese forearc. Shortly after magmatic emplacement of the ophiolite, starved forearc-basin sedimentation began at abyssal depth in the topographic lows of the irregular pillow-basalt substrate. Channelized gravity flows containing clasts of ophiolite layers from basalt to gabbro and serpentinite suggest rough, fault-bounded relief and submarine erosion triggered by tectonic instability. Deposition of volcanoclastic turbidites began at 113–110 Ma as a result of subduction-related igneous activity in the Lhasa terrane initiating rapid topographic

growth of the Asian active margin. The origin of the ophiolitic basement and the topographic growth of the arc source are considered as two critical factors for the birth of the Xigaze forearc basin.

Acknowledgements

We are deeply grateful to the editor An Yin and two reviewers Ryan Leary and Devon Orme for their constructive comments. We thank Xiao-Xiao Ling for help in SIMS zircon dating, and Yue-Heng Yang for LA–ICPMS zircon dating and LA–MC–ICPMS Hf isotopic analyses. This work was financially supported by the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (XDB03010600), and the National Science Foundation of China (projects 41672109 and 41525007).

References

- Aitchison, J.C., Davis, A.M., Liu, J.B., Luo, H., Malpas, J.G., McDermid, I.R., Wu, H.Y., Zhiabrev, S.V., Zhou, M.F., 2000. Remnants of a Cretaceous intra-oceanic subduction system within the Yarlung–Zangbo suture (southern Tibet). *Earth and Planetary Science Letters* 183, 231–244.
- An, W., Hu, X.M., Garzanti, E., BouDagher-Fadel, M.K., Wang, J.G., Sun, G.Y., 2014. Xigaze forearc basin revisited (South Tibet): Provenance changes and origin of the Xigaze Ophiolite. *Geological Society of America Bulletin* 126, 1595–1613.

517 An, W., Hu, X.M., Garzanti, E., 2017. Sandstone provenance and tectonic evolution
 518 of the Xiukang Mélange from Neotethyan subduction to India–Asia collision
 519 (Yarlung-Zangbo suture, south Tibet). *Gondwana Research* 41, 222–234.

520 Boudager-Fadel, M.K., Hu, X.M., Prince, G.D., Sun, G.Y., Wang, J.G., An, W., 2017.
 521 Foraminiferal biostratigraphy and paleoenvironmental analysis of the
 522 mid-Cretaceous limestones in the southern Tibetan Plateau. *Journal of*
 523 *Foraminiferal Research*, in press.

524 Chiu, H.Y., Chung, S.L., Wu, F.Y., Liu, D., Liang, Y.H., Lin, I.J., Iizuka, Y., Xie,
 525 L.W., Wang, Y., Chu, M.F., 2009. Zircon U–Pb and Hf isotopic constraints from
 526 eastern Transhimalayan batholiths on the precollisional magmatic and tectonic
 527 evolution in southern Tibet. *Tectonophysics* 477, 3–19.

528 Chu, M.F., Chung, S.L., Song, B., Liu, D.Y., O'Reilly, S.Y., Pearson, N.J., Ji, J.Q.,
 529 Wen, D.J., 2006. Zircon U–Pb and Hf isotope constraints on the Mesozoic
 530 tectonics and crustal evolution of southern Tibet. *Geology* 34, 745–748.

531 Dai, J.G., Wang, C.S., Polat, A., Santosh, M., Li, Y.L., Ge, Y.K., 2013. Rapid forearc
 532 spreading between 130–120 Ma: Evidence from geochronology and
 533 geochemistry of the Xigaze Ophiolite, southern Tibet. *Lithos* 172–173, 1–16.

534 Dai, J.G., Wang, C.S., Zhu, D.C., Li, Y.L., Zhong, H.T., Ge, Y.K., 2015. Multi-stage
 535 volcanic activities and geodynamic evolution of the Lhasa terrane during the
 536 Cretaceous: Insights from the Xigaze forearc basin. *Lithos* 218–219, 127–140.

- 537 Dickinson, W.R., 1995. In: Busby, C.J., Ingersoll, R.V., (Eds.) Forearc basins,
538 Tectonics of sedimentary basins. Cambridge, MA: Blackwell Science, pp.
539 221–261.
- 540 Dürr, S.B., 1996, Provenance of Xigaze fore-arc basin clastic rocks (Cretaceous, south
541 Tibet). Geological Society of America Bulletin 108, 669–684.
- 542 Einsele, G., Liu, B., Dürr, S., Frisch, W., Liu, G., Luterbacher, H., Ratschbacher, L.,
543 Ricken, W., Wendt, J., Wetzel, A., 1994. The Xigaze forearc basin: Evolution
544 and facies architecture (Cretaceous, Tibet). Sedimentary Geology 90, 1–32.
- 545 Encarnación, J.P., Mukasa, S.B., Obille, E.C., 1993. Zircon U-Pb Geochronology of
546 the Zambales and Angat Ophiolites, Luzon, Philippines: Evidence for an Eocene
547 Arc-Back Arc Pair. Journal of Geophysical Research 98(B11): 19, 991–20, 004.
- 548 Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J.,
549 Huang, Z., 1994. A Mesozoic time scale. Journal of Geophysical Research 99,
550 24051–24074.
- 551 Hébert, R., Bezard, R., Guilmette, C., Dostal, J., Wang, C., Liu, Z., 2012. The
552 Indus–Yarlung Zangbo ophiolites from Nanga Parbat to Namche Barwa
553 syntaxes, southern Tibet: First synthesis of petrology, geochemistry, and
554 geochronology with incidences on geodynamic reconstructions of Neo-Tethys.
555 Gondwana Research 22, 377–397.

556 Hopson, C.A., Mattinson, J.M., Jr., E.A.P., Luyendyk, B.P., 2008. California Coast
 557 Range ophiolite: Composite Middle and Late Jurassic oceanic lithosphere. The
 558 Geological Society of America, Special Paper 438, 1–101.

559 Hou, Z., Duan, L., Lu, Y., Zheng, Y., Yang, Z., Yang, Z., Wang, B., Pei, Y., Zhao, Z.,
 560 and MaCuaig, T.C., 2015. Lithospheric architecture of the Lhasa Terrane and its
 561 control on ore deposits in the Himalayan-Tibetan Orogen. *Economic Geology*
 562 110, 1541–1575.

563 Hu, X.M., Garzanti, E., Moore, T., Raffi, I., 2015. Direct stratigraphic dating of
 564 India-Asia collision onset at the Selandian (middle Paleocene, 59 ± 1 Ma).
 565 *Geology* 43, 859–862.

566 Hu, X.M., Wang, J.G., BouDagher-Fadel, M., Garzanti, E., An, W., 2016. New
 567 insights into the timing of the India–Asia collision from the Paleogene Quxia and
 568 Jialazi formations of the Xigaze forearc basin, South Tibet. *Gondwana Research*
 569 32, 76–92.

570 Huang, W.T, van Hinsbergen, D.J.J., Maffione, M., Orme, D.A., Dupont-Nivet, G.,
 571 Guilmette, C., Ding, L., Guo, Z.J., Kapp, P., 2015. Lower Cretaceous Xigaze
 572 ophiolites formed in the Gangdese forearc: Evidence from paleomagnetism,
 573 sediment provenance, and stratigraphy. *Earth and Planetary Science Letters* 415,
 574 142–153.

575 Ingersoll, R.V., 1979. Evolution of the Late Cretaceous forearc basin, northern and
 576 central California. *Geological Society of America Bulletin* 90, 813–826.

577 Kapp, P., DeCelles, P.G., Leier, A.L., Fabijanic, J.M., He, S., Pullen, A., Gehrels,
578 G.E., 2007. The Gangdese retroarc thrust belt revealed. *GSA Today* 17(7), 4–9.

579 Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., Liu, C.Z., 2009. Zircon U–Pb
580 geochronology and Hf isotopic constraints on petrogenesis of the Gangdese
581 batholith, southern Tibet. *Chemical Geology* 262, 229–245.

582 Leier, A.L., DeCelles, P.G., Kapp, P., Ding, L., 2007a. The Takena Formation of the
583 Lhasa terrane, southern Tibet: The record of a Late Cretaceous retroarc foreland
584 basin. *Geological Society of America Bulletin* 119, 31–48.

585 Leier, A.L., DeCelles, P.G., Kapp, P., Gehrels, G.E., Ding, L., 2007b. Detrital zircon
586 geochronology of Phanerozoic sedimentary strata in the Lhasa terrane and
587 implications for the tectonic evolution of southern Tibet. *Basin Research* 19,
588 361–378.

589 Li, X.H., Liu, Y., Li, Q.L., Guo, C.H., Chamberlain, K.R., 2009. Precise
590 determination of Phanerozoic zircon Pb/Pb age by multi-collector SIMS without
591 external standardization. *Geochemistry, Geophysics, Geosystems* 10, Q04010.
592 doi:10.1029/2009GC002400.

593 Li, X.H., Tang, G.Q., Gong, B., Yang, Y.H., Hou, K.J., Hu, Z.C., Li, Q.L., Liu, Y.,
594 Li, W.X., 2013. Qinghu zircon: A working reference for microbeam analysis of
595 U–Pb age and Hf and O isotopes. *Chinese Science Bulletin* 58, 4647–4654.

596 Liu, T., Wu, F.Y., Zhang, L.L., Zhai, Q.G., Liu, C.Z., Ji, W.B., Zhang, C., Xu, Y.,
597 2016. Zircon U–Pb geochronological constraints on rapid exhumation of the

598 mantle peridotite of the Xigaze ophiolite, southern Tibet. *Chemical Geology* 443,
599 67–86.

600 Maffione, M., Van Hinsbergen, D.J.J., Koornneef, L., Guilmette, C., Hodges, K.V.,
601 Huang, W., Kapp, P., Ding, L., 2015. Forearc hyperextension dismembered the
602 South Tibetan ophiolites. *Geology* 43(6), 475–478.

603 Marsaglia, K.M., Ingersoll, R.V., 1992. Compositional trends in arc-related,
604 deep-marine sand and sandstone: a reassessment of magmatic-arc provenance.
605 *Geological Society of America Bulletin* 104, 1637–1649.

606 Morel, M.L.A., Nebel, O., Nebel-Jacobsen, Y., Vroon, P.Z., 2008. Hafnium isotope
607 characterization of the GJ-1 zircon reference material by solution and
608 laser-ablation MC–ICPMS. *Chemical Geology* 255, 231–235.

609 Murphy, M.A., Yin, A., Harrison, T.M., Dürr, S.B., Chen, Z., Ryerson, F.J., Kidd,
610 W.S.F., Wang, X., Zhou, X., 1997. Did the Indo-Asian collision alone create the
611 Tibetan plateau? *Geology* 25, 719–722.

612 Mutti, E., 1992. *Turbidite Sandstones*. Universita Di Parma, Istituto Di Geologia, 275
613 pp.

614 Nicolas, A., Girardeau, J., Marcoux, J., Dupre, B., Wang, X.B., Cao, Y.G., Zheng,
615 H.X., Xiao, X.C., 1981. The Xigaze ophiolite (Tibet): a peculiar oceanic
616 lithosphere. *Nature* 294, 414–417.

617 O'Dogherty, L. 1994. Biochronology and Paleontology of Mid-Cretaceous
618 Radiolarians from Northern Apennines (Italy) and Betic Cordillera (Spain).
619 Mémoires de Géologie, Université de Lausanne, 21.

620 Orme, D.A., Carrapa, B., Kapp, P., 2015. Sedimentology, provenance and
621 geochronology of the upper Cretaceous-lower Eocene western Xigaze forearc
622 basin, southern Tibet. *Basin Research* 27, 387–411.

623 Orme, D.A., Laskowski, A.K., 2016. Basin Analysis of the Albian–Santonian Xigaze
624 Forearc, Lazi Region, South-Central Tibet. *Journal of Sedimentary Research* 86,
625 894–913.

626 Schweller, W.J., Roth, P.H., Karig, D.E., Bachman, S.B., 1984. Sedimentation history
627 and biostratigraphy of ophiolite-related Tertiary sediments, Luzon, Philippines.
628 *Geological Society of America Bulletin* 95, 1333-1342.

629 Sciunnach, D., Garzanti, E., 2012. Subsidence history of the Tethys Himalaya. *Earth*
630 *Science Reviews* 25, 179–198.

631 Surpless, K.D., Graham, S.A., Covault, J.A., Wooden, J.L., 2006. Does the Great
632 Valley Group contain Jurassic strata? Reevaluation of the age and early
633 evolution of a classic forearc basin. *Geology* 34(1), 21-24.

634 Talling, P.J., Masson, D.C., Summer, E.J., Malgesini, G., 2012. Subaqueous sediment
635 density flows: depositional processes and deposit types. *Sedimentology* 59,
636 1937–2003.

- 637 Wang, C.S., Li, X.H., Liu, Z.F., Li, Y.L., Jansa, L., Dai, J.G., Wei, Y.S., 2012.
638 Revision of the Cretaceous–Paleogene stratigraphic framework, facies
639 architecture and provenance of the Xigaze forearc basin along the Yarlung
640 Zangbo suture zone. *Gondwana Research* 22, 415–433.
- 641 Wang, J.G., Hu, X.M., Garzanti, E. and Wu, F.Y., 2013. Upper Oligocene-Lower
642 Miocene Gangrinboche Conglomerate in the Xigaze Area, Southern Tibet:
643 Implications for Himalayan Uplift and Paleo-Yarlung-Zangbo Initiation. *Journal*
644 *of Geology* 121(4), 425–444.
- 645 Wang, J.G., Hu, X.M., Garzanti, E., Ji, W.Q., Liu, Z.C., Liu, X.C., Wu, F.Y.,
646 submitted for publication. Early Cretaceous topographic growth of the
647 Lhasaplano, Tibetan Plateau: Constraints from the Damxung Conglomerate.
648 *Journal of Geophysical Research*.
- 649 Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon
650 reference materials for in situ Hf isotope determination. *Geostandards and*
651 *Geoanalytical Research* 29, 183–195.
- 652 Wu, F.Y., Yang, Y.H., Xie, L.W., Yang, J.H., Xu, P., 2006. Hf isotopic compositions
653 of the standard zircons and baddeleyites used in U–Pb geochronology. *Chemical*
654 *Geology* 234, 105–126.
- 655 Wu, F.Y., Ji, W.Q., Liu, C.Z., Chung, S.L., 2010. Detrital zircon U–Pb and Hf
656 isotopic data from the Xigaze fore-arc basin: Constraints on Transhimalayan
657 magmatic evolution in southern Tibet. *Chemical Geology* 271, 13–25.

658 Xie, L.W., Zhang, Y.B., Zhang, H.H., Sun, J.F., Wu, F.Y., 2008. In situ simultaneous
 659 determination of trace elements, U–Pb and Lu–Hf isotopes in zircon and
 660 baddeleyite. *Chinese Science Bulletin* 53, 1565–1573.

661 Yin, J.X., Wen, C.F., Sun, Y.Y., 1988. Late Jurassic to Late Cretaceous trench-slope
 662 deposits in Yarlung-Zangbo suture zone–Chongdui Formation. *Memoirs of the*
 663 *Institute of Geology, Chinese Academy of Science* 3, 158–176 (in Chinese).

664 Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S.L., Hou, Z.Q., Wang, L.Q.,
 665 Wu, F.Y., 2011. The Lhasa Terrane: record of a microcontinent and its histories
 666 of drift and growth. *Earth and Planetary Science Letters* 301, 241–255.

667 Ziabrev, S., Aitchison, J., Abrajvitch, A., Davis, A., Luo, H., 2003. Precise
 668 radiolarian age constraints on the timing of ophiolite generation and
 669 sedimentation in the Dazhuqu terrane, Yarlung-Tsangpo suture zone, Tibet.
 670 *Journal of the Geological Society, London* 160, 591–599.

671

FIGURE CAPTIONS

Fig. 1. Geological map of the Xigaze area (south Tibet) (modified after Dai et al., 2015) with location of the studied sections (1—Qunrang-1; 2—Qunrang-2; 3—Naxia; 4—Polio) and the field photos shown in Figure 3. Inset shows tectonic domains of the Tibetan Plateau (SG—Songpan-Ganze; QT—Qiangtang; LS—Lhasa; HL—Himalaya) and the two magmatic belts of the Lhasa terrane.

Fig. 2. Lithostratigraphy of the studied sections. Stratigraphic position of samples and SIMS age of dated tuffs are shown. Ages are given with 2σ error.

Fig. 3. Field photographs. A–E are from the Qunrang-1 section. A: Depositional contact between chert at the base of the Chongdui Formation and underlying basalts of the Xigaze ophiolite. B: Thin-layered white tuffs in the chert unit. C: Conformable contact between the siliceous mudrocks and the turbidites, and lenticular ophioliticlastic conglomerate in the siliceous mudrock unit. D: Ophioliticlastic conglomerate (B—Basalt; D—Diabase; G—Gabbro; S—Serpentinite). E: Thick tuff layer interbedded within turbidites of the upper member. F: Interbedded purplish red chert and basaltic breccia at the base of Qunrang-2 section. G–J are from the Naxia section. G: Depositional contact between the Chongdui Formation and underlying pillow basalts. H: Thin tuff layers interbedded with greenish siliceous mudrocks at the base of the Chongdui Formation. I: Interbedded tuffaceous chert and siliceous mudrocks of the lower member. J: Submarine gravity flow with sandstone boulders in the upper member. K–L are from the Polio section. K: Depositional contact between the chert and the basalts of the Xigaze ophiolite. L: Conformably transition from the

lower chert member to the upper turbiditic member. Arrows indicate the direction of up-section.

Fig. 4. Microphotographs from the Chongdui Formation. A: radiolarian chert (Qunrang-1); B: felsic tuff (Qunrang-1); C–F: volcaniclastic sandstones from Qunrang-1, Qunrang-2, Naxia, and Polio sections. Bt—Biotite; Lu—Serpentine fragment; Lv—Volcanic rock fragment; Pl—Plagioclase; Q—Quartz.

Fig. 5. A: Plots of $\epsilon_{\text{Hf}}(t)$ vs. age of zircon crystals from tuffs. B: Hf isotopes of zircon crystals from Lower Cretaceous magmatic rocks of the Lhasa terrane are plotted for comparison and provenance interpretation. Data was summarized in Hou et al. (2015).

Fig. 6. Probability density plot of U–Pb ages (A and C) and $\epsilon_{\text{Hf}}(t)$ vs. age plot of detrital zircons from sandstones (sample position indicated in Fig. 2).

Fig. 7. Chronostratigraphic correlation of measured sections (UA, Unitary Association of radiolarian after O’Dogherty, 1994; chronostratigraphic scale after Gradstein et al., 1994). Radiolarian results are from Ziabrev et al. (2003). SIMS dates of zircon from the Xigaze ophiolite (data summarized in Liu et al., 2016) are plotted for comparison.

Fig. 8. Paleogeographic reconstruction (not to scale) shows the birth and earliest evolution of the Xigaze forearc basin (Modified after the paleogeographic figures in Orme et al., 2015; Orme and Laskowski, 2016). A: After the Xigaze ophiolite formed in the Gangdese forearc between 131 and 124 Ma, topographic depressions on the newly formed ophiolitic crust were filled by chert and siliceous mudrocks documenting the initial starved stage of forearc-basin sedimentation between ca. 123 and 113 Ma. Occurrence of ophiolite-derived pebbles, cobbles and boulders indicates

716 a very rough, unstable forearc-basin substratum with considerable local submarine
717 relief. Meanwhile, carbonate platform was widely developed on the Lhasa terrane,
718 indicating submarine conditions and low relief in most of the Lhasa terrane. B:
719 Deposition of volcanoclastic turbidites initiated in the Xigaze forearc basin at ca. 113
720 to 110 Ma, reflecting initial topographic growth on the Lhasa terrane. The
721 paleogeography on the Lhasa terrane was referenced from ([Leier et al., 2007a](#); [Orme](#)
722 [and Laskowski, 2016](#); [Boudager-Fadel et al., 2017](#); [Wang et al., submitted for](#)
723 [publication](#)).

APPENDIX

Figure DR1. U–Pb concordia diagrams and weighted means of $^{206}\text{Pb}/^{238}\text{U}$ ages for zircons crystals contained in tuffs. MSWD—mean square of weighted deviates.

Figure DR2. A: Simplified geological map of Sangsang area modified after the Figure 1c of Huang et al. (2015). The Sangsang ophiolite lies under a southward thrust with the Padana Formation which was deposited during the latest evolution stage of the Xigaze forearc basin in the hanging wall. B: The contact between the Padana Formation and the Sangsang ophiolite. Note the strata transit up-section to red delta plain facies (right behind). C: Fault contact between the Padana Formation and the serpentinitized peridotites. Note the fault gouge.

Figure DR3. A: Simplified geological map of the Qunrang section in the Xigaze area modified after the Figure 1c of Maffione et al. (2015). The Qunrang ophiolite northward overthrust the Ngamring Formation of the Xigaze forearc strata. The location of this map was shown in Figure 1. B: Slickensides on the fault plane of the sheeted sills. C: Strongly fractured rodingite dykes in the brecciated zone between the Ngamring Formation and the serpentinitized peridotites.

Table DR1. SIMS U–Pb data of zircon crystals contained in tuffs.

Table DR2. LA-ICP-MS U–Pb data of zircon grains contained in sandstones.

Table DR3. Hf isotopic data of zircons.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

**A: Starved forearc-basin sedimentation
(ca. 123-113 Ma)**

**C: Initiation of clastic sedimentation
(ca. 113-110 Ma)**