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ZIRCON U–Pb AND Hf ISOTOPIC CONSTRAINTS ON THE ONSET TIME OF INDIA-ASIA COLLISION

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ABSTRACT. The time of initial collision between India and Asia has been extremely controversial despite the fact that it is vital to constraining the orogenesis and subsequent evolution of the Himalayas and Tibetan Plateau. Here we report U–Pb and Hf isotope analysis of detrital zircons from two principal foreland basins, that is, the Sangdanlin and Gyangze basins respectively in the western and central parts of southern Tibet. Our data suggest that Asian-derived clastic sediments started contributing to sedimentation on the Indian continental margin earlier than generally thought, at ~60 Ma in both basins near the Yarlung-Zangbo Suture Zone. In southern Tibet, no evidence for the existence of an intra-oceanic arc within the Neotethys is observed. We conclude that ~60 Ma can be used to constrain the onset time of the India-Asia collision, at least in central Tibet. After this initial collision, closure of the Neotethys propagated both westward and eastward, with the final closure occurring at ~50 and ~45 Ma in northwestern and eastern Himalayas, respectively. Our conclusion differs significantly from the previous view that the India-Asia collision may have started in northwestern Himalaya and propagated eastward with diachronous suturing.

Key words: Detrital zircon, U–Pb age, Hf isotopes, India-Asia collision

INTRODUCTION

The India-Asia collision is the largest continental collision event during the past 500 Ma on the Earth (Allègre and others, 1984; Yin and Harrison, 2000). The collision and subsequent rising of Tibetan Plateau had a profound influence on the drainage patterns of the major rivers in Asia, the oceanography of the surrounding seas, the continental climate and the history of faunal extinctions (Molnar and others, 1993; Clift and others, 2008). However, the precise collision time is not well determined despite the fact that numerous approaches have been applied, which had yielded varying ages ranging from as old as 70 to as young as 34 Ma (Rowley, 1996; Yin and Harrison, 2000; Aitchison and others, 2007; Khan and others, 2009; Najman and others, 2010). Commonly employed approaches for constraining collision include paleomagnetism (Patrait and Achache, 1984; Besse and Courtillot, 1988; Klootwijk and others, 1992; Patzelt and others, 1996; Chen and others, 2010a; Dupont-Nivet and others, 2010; Liebke and others, 2010; Tan and others, 2010; Yi and others, 2011; Meng and others, 2012), floral and faunal distributions (Jaeger and others, 1989; Prasad and others, 1994; Upadhyay and others, 2004; Clementz and others, 2011), cessation of marine facies and change of sedimentation patterns (Garzanti and others, 1996; Willems and others, 1996; Searle and others, 1997; Green and others, 2008; Zhang and others, 2012b), development of flexure-related unconformities in the suture zone and Tethyan Himalaya (Beck and others, 1995; Ding and others, 2005; Hu and others, 2012), the timing of eclogite metamorphism caused by continental subduction (Tonarini and others, 1993; de Sigoyer and others, 2000; Kaneko and others, 2003; Leech and others, 2005, 2007; Donaldson and others, 2013) and the end of Gangdese

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I-type granitoid injection (Searle and others, 1987; White and others, 2012; Bouihol and others, 2013).

The different approaches listed above represent different aspects in an ongoing complex collisional process. Some of them are minimum estimates, while others are based on indirect evidence. For example, changes in sedimentation may be equally well explained by southward obduction of Neotethyan intraoceanic rocks, including ophiolitic fragments and subduction-accretion complexes, onto the northern margin of India during Late Cretaceous–early Tertiary time prior to India-Asia collision (Ding and others, 2005; Bouihol and others, 2013). Generally, initial collision is defined as the time of disappearance of the oceanic lithosphere and first contact between continental crustal blocks. After initial collision, the rocks of the active continental margin are typically uplifted, eroded and transported into the foreland basin on the opposing passive margin. Therefore, the appearance of Asian-derived detritus on the Indian continental margin should provide direct evidence of this collision (Burbank and others, 1996; Wu and others, 2007; Najman and others, 2008, 2010; Cai and others, 2011; Wang and others, 2011).

During the past decade, several methods have been employed to constrain the nature of the source of the sedimentary rocks in the foreland and suture zone basins along the northern edge of the Indian continental margin, including the Nd–Pb isotopic character of whole-rocks and their constituent minerals (Clift and others, 2001; DeCelles and others, 2004; Henderson and others, 2010a; Hu, 2012), the geochemistry of clastic mineral grains (Qayyum and others, 2001; Zhu and others, 2005a; Henderson and others, 2010a; Cai and others, 2011; Wang and others, 2011), and the geochronological dating of detrital minerals (Najman and others, 2001; White and others, 2001; DeCelles and others, 2004; Wu and others, 2007; Henderson and others, 2010a; Aitchison and others, 2011).

Among these methods, the U–Pb age spectra of detrital zircons in clastic sedimentary rocks has been especially effective in evaluating potential source regions for sediments, which in turn can be used to define paleogeographic units (terrains), and constrain models for basin and orogen development, as well as possible feedback mechanism between these processes (Najman, 2006). Moreover, it has been demonstrated that zircon Lu–Hf isotope systematics combined with U–Pb dating can be a powerful tool for deciphering the sediment source. Because their ^{176}Lu/^{177}Hf ratios are mostly less than 0.001, which means that time-integrated changes to the ^{176}Hf/^{177}Hf ratio as a result of *in situ* decay of ^{176}Lu proceed at virtually negligible rates within zircon grains (Kinny and Mass, 2003). Considering the well-known resilience of zircons to surficial weathering, transportation, and sedimentation processes, these minerals can effectively preserve the initial ^{176}Hf/^{177}Hf ratio of the source at the time of crystallization. In contrast to the crystallization ages obtained from U–Pb isotopes, Lu–Hf isotopes can provide crust formation ages for the igneous source of the dated grains because Lu–Hf ratios are fractionated only during crust-formation processes (Kinny and Mass, 2003). Recent studies show that combined U–Pb ages and Hf isotopes of detrital zircons can effectively elucidate the sources of detrital zircon grains in sedimentary and meta-sedimentary rocks (Wu and others, 2007, 2010; Liang and others, 2008; Cina and others, 2009; Ravikant and others, 2011). Thus, the Hf isotopic composition of zircon can be utilized as a geochemical tracer of a host rock's origin in exactly the same way that whole-rock Nd isotopes have been used, that is, to estimate degrees of crustal recycling.

In this study, we conducted a comprehensive U–Pb and Lu–Hf isotopic study of detrital zircons from Mesozoic–Cenozoic sedimentary rocks exposed in the Tethyan Himalaya south of the Yarlung-Zangbo suture, including those from the Sangdanlin and Gyangze Basins in southern Tibet (fig. 1). Our data indicate that the initial

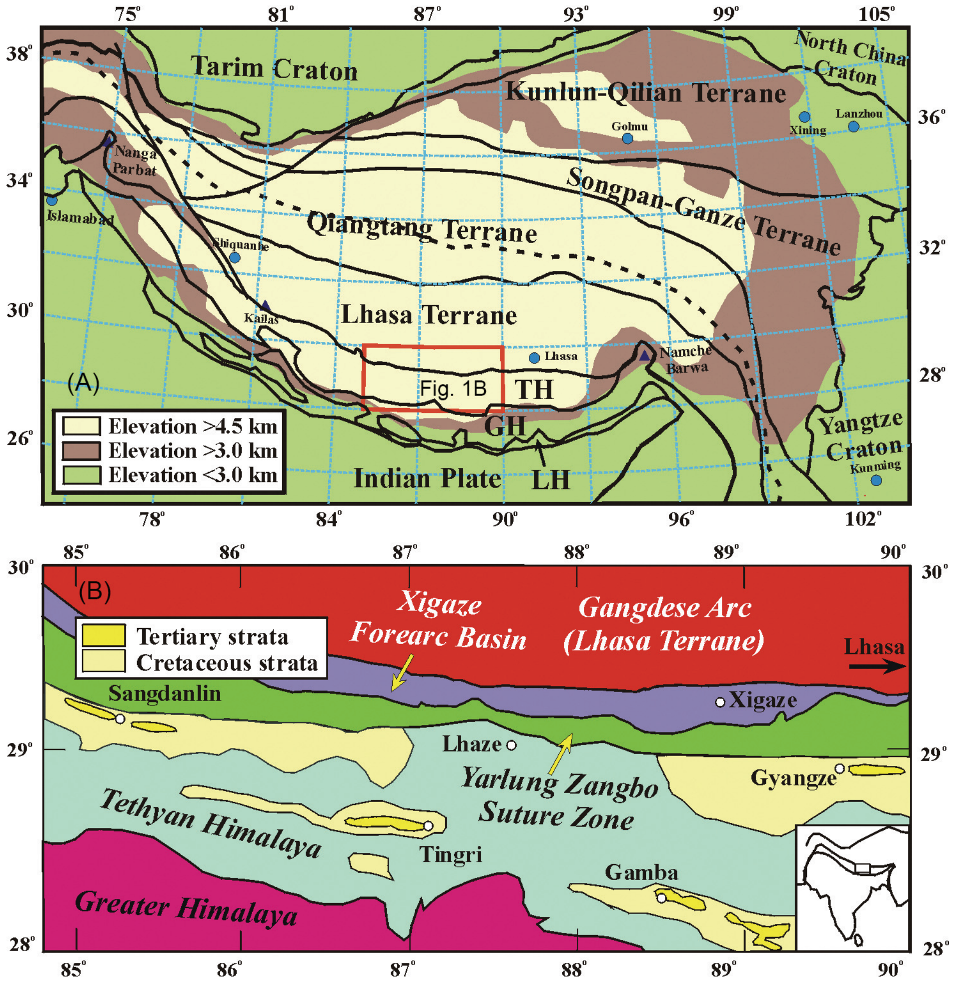

Fig. 1. (A) Tectonic divisions of the Tibetan plateau (TH: Tethyan Himalaya; GH: Greater Himalaya, LH: Lesser Himalaya). (B) Simplified tectonic map of southern Tibet based on Ding and others (2005). The inserted map shows location of the study area.

collision of India and Asia took place at ~60 Ma in central Tibet, and propagated to both east and west sides through time. The final suturing finished at ~50 and 45 Ma in the northwest and eastern Himalaya, respectively, comparable to the previous estimate of 55 ± 5 Ma (Garzanti, 2008), but not as young as the 34 Ma age recently suggested by Aitchison and others (2007).

GEOLOGICAL SETTING

Regional Geology

The Tibetan Plateau is composed of the Asian plate to the north and the Indian plate to the south, separated by the Indus-Yarlung-Zangbo suture between them (fig. 1A). The Asian plate is subdivided into the Kunlun-Qilian, Songpan-Ganze, Qiangtang and Lhasa terranes, while the Indian plate can be split into the Tethyan, Higher and Lesser Himalayans, as well as undeformed cratonic India. As for the area of South Tibet studied here, it is composed of a series of terranes that are known from north to south as (1) Lhasa terrane, (2) Xigaze forearc, (3) Yarlung-Zangbo suture zone, (4) Tethyan Himalaya and (5) Greater (High) Himalaya (fig. 1B). Located north of the Yarlung-Zangbo suture zone, the Lhasa Terrane is a part of the Asian continent. The Cambrian and older orthogneisses, located in the northern Lhasa Terrane, represent the terrane basement. Paleozoic–Mesozoic sedimentary rocks are widely distributed, especially in the northern Lhasa Terrane. During Mesozoic–Cenozoic time, the Lhasa Terrane was characterized by voluminous granitic intrusions and related volcanic eruptions. In particular, the southern Lhasa Terrane comprises Jurassic–early Tertiary calc-alkaline granitoids of the Gangdese Batholith (Chung and others, 2005; Wen and others, 2008; Chiu and others, 2009; Ji and others, 2009; Zhu and others, 2011a) and Cretaceous to Tertiary non-marine volcanic sequences of the Linzizong Formation (Zhou and others, 2004; Chung and others, 2005; Lee and others, 2007, 2009; Mo and others, 2008). This Gangdese Arc is widely attributed to northward subduction of Neotethyan oceanic lithosphere beneath the southern Asian continental margin (Allègre and others, 1984). However, the presence of Oligocene and Miocene arc-like granitoids within the Gangdese arc cautions using the age of the youngest arc magmatism as a proxy for the time of collision initiation (Yin and Harrison, 2000; Bouihol and others, 2013). Although the isotopic data is scarce for this unit, the available data show that the Gangdese Batholith is characterized by low initial Sr and high Nd–Hf isotopic values indicative of significant growth of juvenile continental crust (Ji and others, 2009; Zhu and others, 2011a, and references therein).

South of the Gangdese arc, sedimentary sequences deposited in a forearc basin along the southern margin of Asia consist of the deep-water, turbidite Cretaceous Xigaze Group and the shallow-water Qubeiya Formation, as well as the Paleocene to lower Eocene foraminifera-bearing Tso-Jiangding Group (fig. 1B, Dürr, 1996; Wang and others, 2012a). Detrital zircon U–Pb and Lu–Hf isotopic studies indicate that the Xigaze forearc sedimentary rocks were deposited during 116 to 65 Ma, with the Jurassic–Cretaceous (190-80 Ma) arc being the major source of sediments (Wu and others, 2010).

The Yarlung-Zangbo suture zone marks the contact between Asian igneous and sedimentary rocks to the north and Indian continental margin strata of the Tethyan Himalaya to the south (Tapponnier and others, 1981; Yin and Harrison, 2000). The suture is characterized by a generally narrow (<15 km), approximately east-west belt of oceanic rocks, which represents offscraped remnants of the Neotethys Ocean, likely a preserved subduction channel to an erosive active continental margin (Draut and Clift, 2013). The main components include Jurassic–Cretaceous ophiolites, mélange units and slices of what has been interpreted as an intraoceanic arc (Nicolas and others, 1981; Aitchison and others, 2007).

The Tethyan Himalaya consists of low-grade metasedimentary and sedimentary rocks of Cambrian–Eocene age that were originally deposited along the passive margin of northern India (fig. 1B). Precambrian–Cambrian granites crop out in a series of metamorphic core complexes, in which leucogranites were emplaced at ~44 to 10 Ma (Zeng and others, 2011; Zhang and others, 2012a; Aikman and others, 2012). The Cretaceous–lower Tertiary marine sedimentary sequences in this unit have been divided into northern and southern units based on differences in lithology (Ding and others, 2005). The southern unit, including those in Gamba and Tingri, is composed mainly of carbonate and clastic sedimentary rocks (Zhu and others, 2005a; Najman and others, 2010; Zhang and others, 2012b). The strata of the northern unit are mainly exposed around in Gyangze and Sangdanlin and are composed of sandstones, shales, and limestones (fig. 1B, Li and others, 2005a; Ding and others, 2005; Wang and others, 2011).

The Greater Himalaya is mainly composed of amphibolite facies metamorphosed Proterozoic metasedimentary rocks intruded locally by early Paleozoic granites (Gehrels and others, 2003). Zircon U–Pb isotopic dating suggested that this unit is characterized by two separate stages of magmatism at ~0.5 and 0.8 to 1.2 Ga (Parrish and Hodges, 1996; DeCelles and others, 2000; Gehrels and others, 2003; Myrow and others, 2003; Richards and others, 2005). Since the onset of India-Asia collision, the Greater Himalaya has been subjected to Barrovian metamorphism. Burial and heating continued until at least 25 to 30 Ma, culminating in crustal melting and emplacement of leucogranites, aged mostly between 23 to 12 Ma (Le Fort, 1996).

Stratigraphy of the Suture Zone Basins

The samples considered in this study were collected from the Sangdanlin and Gyangze Basins in the northern Tethyan Himalaya, south to the Yarlung-Zangbo Suture Zone (fig. 1B). According to field investigation (Ding, 2003; Ding and others, 2005; Chan, ms, 2006; Wang and others, 2011), the strata in the Sangdanlin Basin can be subdivided into the Upper Cretaceous Zongzhuo Formation, Paleocene Sangdanlin and Paleocene–Eocene Zheya Formations (fig. 2A). The Zongzhuo Formation is mostly composed of massive quartz sandstone. The Sangdanlin Formation conformably overlies the Zongzhuo Formation (also named as the Denggang Formation, Wang and others, 2011), which is believed to have been deposited at 68 to 70 Ma (Ding and others, 2005; Chan, ms, 2006). The lower part of the Sangdanlin Formation consists of chert, siltstone and mudstone; whereas the upper part of the Sangdanlin Formation is characterized by thick-bedded sandstone and conglomerate. Spinels were identified in thin sections of sandstones from the Sangdanlin Formation, which were revealed to have compositions similar to spinels found in the Yarlung-Zangbo ophiolites (Ding and others, 2005). However, the spinel is not found in sandstones of the underlying Cretaceous Zongzhuo Formation. Radiolarian fossils in the thin layers of cherty siltstone indicate that the Sangdanlin Formation was deposited between foraminifera zones RP1 and RP7 (~65-55 Ma, Ding and others, 2005; Chan, ms, 2006). The Zheya Formation is mostly composed of massive sandstone. As a result, the Sangdanlin Formation has often been considered as the earliest syn-collisional sediment deposited on the Indian passive continental margin in this area (Ding and others, 2005; Chan, ms, 2006). In this study, twelve samples within and above the Sangdanlin Formation were collected for U–Pb and Hf isotopic analyses (fig. 1B).

The Gyangze Basin is located in the eastern Northern Tethyan Himalaya (fig. 1B) and characterized by Paleozoic–Paleocene marine sedimentary rocks. The Mesozoic–Cenozoic strata can be subdivided into Nieru (Upper Triassic), Ridang (Lower Jurassic), Zhela (Middle Jurassic), Weimei (Upper Jurassic), Gyabula/Jiabula (Lower Cretaceous), Chuangde (Upper Cretaceous), Zongzhuo (Upper Cretaceous, Maastrichtian), and Jiachala (Paleocene-Eocene) formations. Clastic sedimentary rocks can be recognized in most of these formations. The Weimei Formation (~100 m thick) is composed of a lower shale-limestone interval and an upper shale-sandstone. The Gyabula Formation (~1500 m thick) is composed of black and calcareous shales with interlayered sandstone deposited during the Berriasian–Coniacian (145-86 Ma) (Wang and others, 2000). The overlying Chuangde Formation [<100 m in thick, Upper Cretaceous Oceanic Red Beds (CORBs)] and has a thickness of 30 m dominated by red shale and marlstone. Foraminifera and nannofossils indicate a Santonian–Campanian age (86-71 Ma) of deposition (Wan and others, 2005), although a more recent investigation suggested that sedimentation could be young as early Maastrichtian (71-66 Ma) (Li and others, 2011a). The Zongzhuo Formation is about 2000 m thick, and predominately composed of dark shale enclosing variable olistoliths of sandstone, limestone and chert. This appearance resulted in names such as “wildflysch” or “sedimentary mélange” being applied (Tapponnier and others, 1981; Wu and Wang,

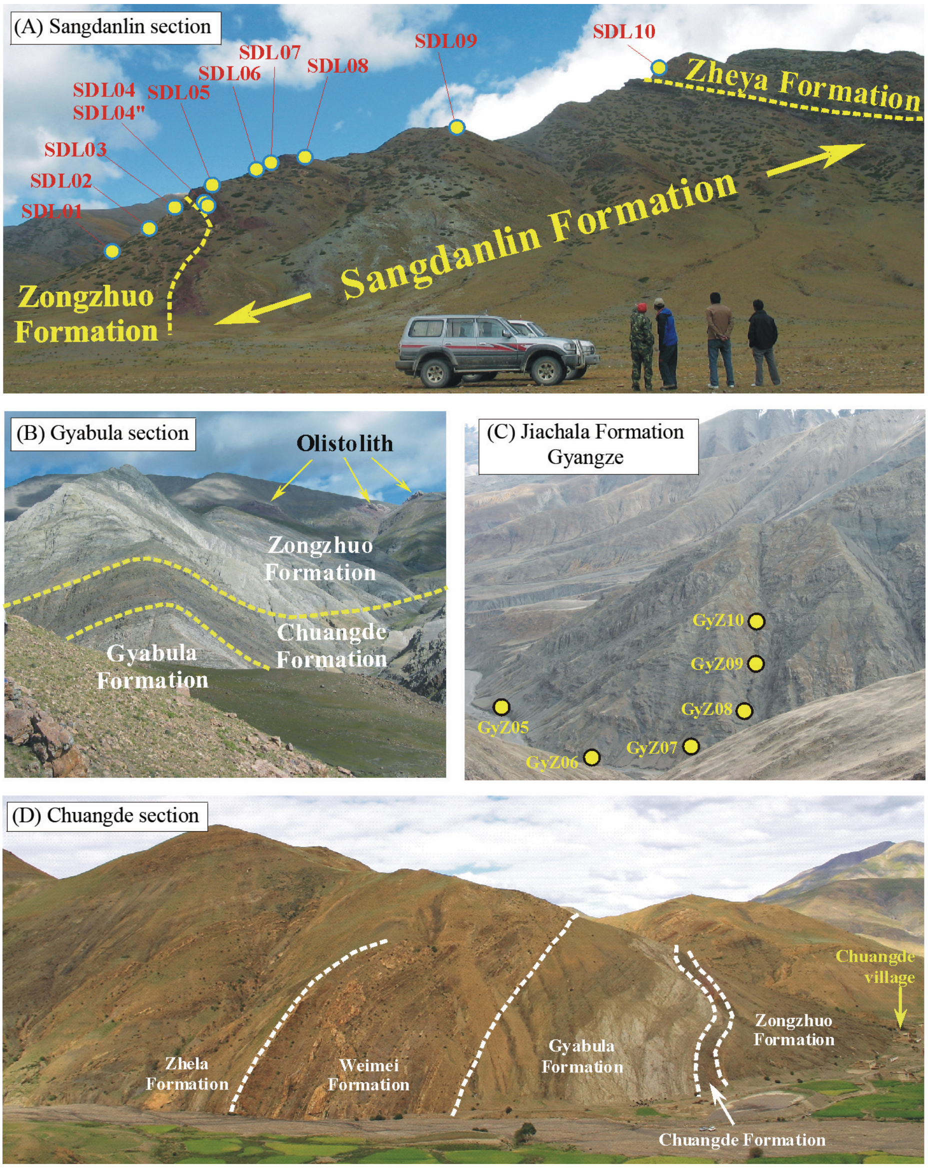

Fig. 2. Stratigraphic sections studied in the paper. (A) Sangdanlin section in Saga; (B) Gyabula section in Gyangze; (C) Jiachala Formation at top of the Zongzhuo Formation in Gyabula section, Gyangze; and (D) Chuangde section in Gyangze.

1981; Yu and others, 1984; Liu and Einsele, 1996; Lian, 1998; Li and others, 2005b). Most researchers agree that this formation was deposited during the Maastrichtian (Wu and Li, 1982; Li and others, 2009a, 2009b, 2011a), although it is possible that the deposition age of this formation may extend to the Paleocene (66-56 Ma) (Burg and Chen, 1984; Searle and others, 1987; Liu and Aitchison, 2002), based on the presence of young radiolarians. However, at the present time these fossils have not been verified in later detailed field investigation (Cai and others, 2011).

It has been proposed that the Zongzhuo Formation might be a tectonic mélange in the Gyangze Basin (Searle and others, 1987; Liu and Aitchison, 2002), but this interpretation is at odds with observations of sedimentary structures and the relationship between the exotic blocks and turbiditic matrix (Yu and others, 1984; Cai and others, 2011). Overlying the Zongzhuo Formation, the Paleocene Jiachala Formation is characterized by thick (~3000 m) sandstone, siltstone and conglomerate with minor shale and marls.

In this study, sixteen samples were collected from two sections for analyses. In the Gyabula section (fig. 2B), the sandstone samples were taken from the Upper Jurassic Weimei (GyZ01), Lower Cretaceous Gyabula (GyZ02) and Upper Cretaceous–Lower Paleocene Zongzhuo (GyZ03 and GyZ04) formations. Six sandstone samples were also collected from the Paleocene–Eocene Jiachala Formation (fig. 2C). For the Chuangde section (fig. 2D), one of the best studied Mesozoic–Cenozoic stratigraphic sections of the Tethyan Himalaya in southern Tibet (Wu and Wang, 1981; Wu and Li, 1982; Wan and others, 2005; Li and others, 2005b), two sandstone samples were collected to verify the obtained data and conclusions from the Gyabula section. The stratigraphic contact of these samples is shown in figure 3.

ANALYTICAL TECHNIQUES

Zircon crystals were obtained from crushed rock using a combination of heavy liquid and magnetic separation techniques. Individual crystals were hand picked, mounted in epoxy resin and polished to remove the upper one third of the grain. Cathodoluminescence (CL) images were obtained using a CAMECA electron microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing, in order to identify internal structures and choose potential target sites for U–Pb and Hf analyses. The working conditions of the CL imaging were 15 kV. Isotopic measurements were carried out at the MC–ICPMS laboratory of the IGGCAS. An Agilent 7500a quadrupole Inductively Coupled Plasma Mass Spectrometer (Q–ICPMS) and a Neptune multi-collector (MC)–ICPMS were used for simultaneous collection of U–Pb isotopes, trace elements and Lu–Hf isotopes with an attached 193 nm Excimer ArF laser-ablation system (GeoLas Plus). During analyses, the ablated aerosol was carried by helium and split into two transport tubes using a three-way pipe and so simultaneously introduced into the Q–ICPMS and MC–ICPMS. The proportion of ablated material carried into the two instruments was controlled by three mass flow controllers. Our experiments indicate that there is no significant mass fractionation when different proportions of ablated material were carried into the Q–ICPMS and MC–ICPMS (Xie and others, 2008).

Before analysis, each sample surface was cleaned with ethanol to eliminate possible contamination. Every ten sample analyses were followed by measurements of one zircon 91500, one GJ-1 and one NIST SRM 610 standard. ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ratios were calculated using GLITTER 4.0. Harvard zircon 91500 was used as a calibration standard (Griffin and others, 2008). ^{207}Pb/^{235}U ratio was calculated from the values of ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U (^{235}U = ^{238}U/137.88). The relative standard deviations of reference values for 91500 were set at 2 percent. Common Pb was corrected according to the method proposed by Anderson (2002). The weighted mean U–Pb ages and concordia plots were processed using ISOPLOT 3.0. During data acquisition, analyses of the zircon standard GJ-1 as an unknown yielded a weighted ^{206}Pb/^{238}U age of 607 ± 3 Ma (MSWD=0.1, n=77), which is in good agreement with the recommended ID-TIMS age of 608.53±0.37 Ma (Jackson and others, 2004). The dataset can be found in the Appendix I (http://earth.geology.yale.edu/~ajs/SupplementaryData/2014/01Wu.xlsx). For statistical purposes, zircons >1000 Ma with discordance <10 percent and those <1000 Ma with discordance <20 percent were considered as usable.

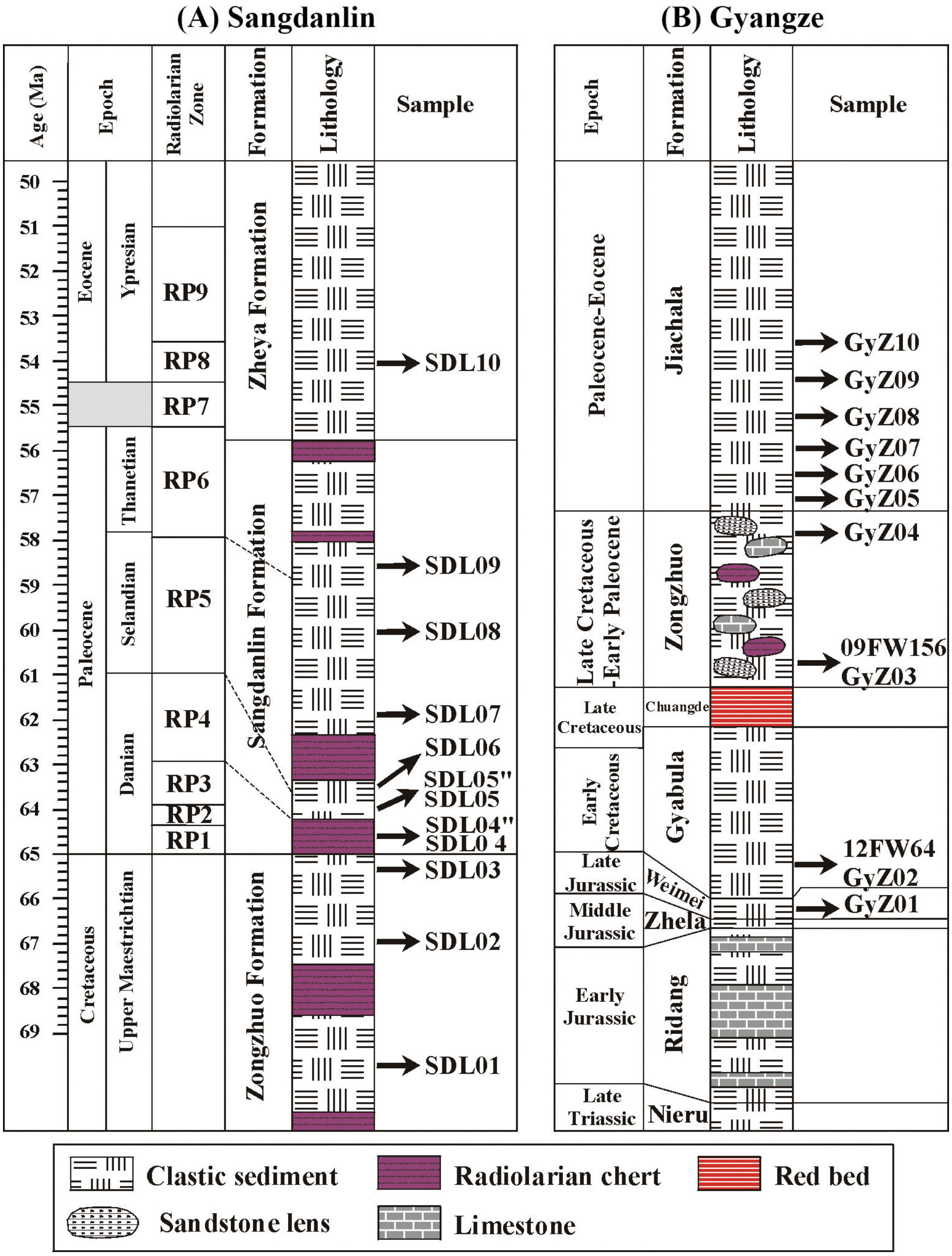

Fig. 3. Stratigraphic columns of the (A) Sangdanling and (B) Gyangze (Gyabula and Chuangde) sedimentary Formations.

The Neptune MC–ICPMS was used in this study for zircon Hf isotopic measurements. During laser ablation analyses, the isobaric interference of ^{176}Lu on ^{176}Hf is not considered because of the extremely low ^{176}Lu/^{177}Hf in zircon (normally <0.002). Interference of ^{176}Yb on ^{176}Hf is corrected by measuring ^{173}Yb/^{171}Yb ratio, calculating the fractionation coefficient (b_{Yb}), and then extracting the contribution of ^{176}Yb to ^{176}Hf (Wu and others, 2006). Standard zircon 91500 was used for external correction assuming that its ^{176}Hf/^{177}Hf value is 0.282305 (Wu and others, 2006). During this analytical session, standard GJ-1 was used as an unknown sample and yielded a ^{176}Hf/^{177}Hf value of 0.282025 ± 37 (2SD n=86) which is within error of values obtained by solution method (Morel and others, 2008). The Hf isotopic data of dated zircons are listed in the Appendix I (http://earth.geology.yale.edu/~ajs/SupplementaryData/2014/01Wu.xlsx).

ANALYTICAL RESULTS

Sangdanlin Basin

During our study, zircons from three sandstones (SDL01, SDL02 and SDL03) from the Zongzhuo Formation, eight sandstones (SDL04, SDL04″, SDL05, SDL05″, SDL06 SDL07, SDL08 and SDL09) from the Sangdanlin Formation and one sample (SDL10) from the Zheya Formation were selected for laser U–Pb and Lu–Hf isotopic analyses (fig. 1B). Under the microscope, the separated zircons can be classified into two subgroups according to their crystal morphology. Dark brown zircons are mostly rounded, with grain-sizes of ~100 mm and show complex internal textures under Cathodoluminescence (CL) imaging, indicating long transport distance, consistent with variable/mixed origins. In contrast, light yellow grains are mostly euhedral in shape with grain-size of 300 to 100 mm, length/width ratios of ~2 and clear zoning internal textures, suggestive of their derivation from nearby granitic sources. The analytical data can be found in Appendix I (http://earth.geology.yale.edu/~ajs/SupplementaryData/2014/01Wu.xlsx).

Zongzhuo Formation (Cretaceous).—Zircons from the three Zongzhuo Formation samples are mostly purple to dark brown in color, show irregular shapes and have grain-sizes of ~100 mm. These grains sometimes show oscillatory zoning. Ninety-five, 78 and 75 U–Pb analyses have been obtained for samples SDL01, SDL02 and SDL03, respectively, and all of them show a similar age pattern with ages ranging from 3250 ± 10 to 457 ± 11 Ma (fig. 4). Statistics show major age peaks at 630 to 500 and 1200 to 800 Ma with some scattered ages between 3.2 to 1.4 Ga. This age pattern is similar to those already documented from the Miocene strata of the Siwalik Group in Nepal (DeCelles and others, 2004). Similarly, zircons from the three samples show identical Hf isotopic characteristics (figs. 4A-4I).

Sangdanlin Formation (Paleocene).—Zircons from the Sangdanlin Formation are more complicated than those from the Zongzhuo Formation in terms of their shape, internal structure and age distribution pattern. Among the seven samples analyzed, three samples (SDL04, SDL06 and SDL07) show similar zircon crystal morphology and internal zoning, age patterns and Hf isotopes to those from the Zongzhuo Formation (figs. 4J-4L, and figs. 5A-5I). However, sample SDL04″, a garnet-bearing sandstone, contains much higher proportions of Jurassic–Cretaceous zircon (19 out of 91 grains, figs. 4M-4N). These Mesozoic zircons show characteristically negative $\varepsilon_{Hf}(t)$ values of −1.5 to −6.8 with an exception of +0.6 (fig. 4O). The remaining four samples (SDL05, SDL05″ SDL08 and SDL09) have higher proportions of yellow-colored zircons, and show much younger ages (figs. 5J-5R). In sample SDL05, 65 out of 87 zircons (75%) dated as Paleocene–Mesozoic, with ages ranging from 62 ± 1 to 203 ± 13 Ma. In order to check the reliability of these analyses, a duplicate sample (SDL05″) was collected for further analyses, which show that 94 out of 99 zircons are Mesozoic–Cenozoic, with ages between 57 ± 2 and 217 ± 4 Ma. In samples SDL08 and SDL09, 86 out of 92 (93%) and 47 out of 77 (61%) grains show Mesozoic–Cenozoic U–Pb ages, which rangs from 70 ± 8 to 204 ± 3 Ma and from 59 ± 2 to 193 ± 19 Ma, respectively. These young zircons have characteristically high radiogenic Hf isotopic compositions

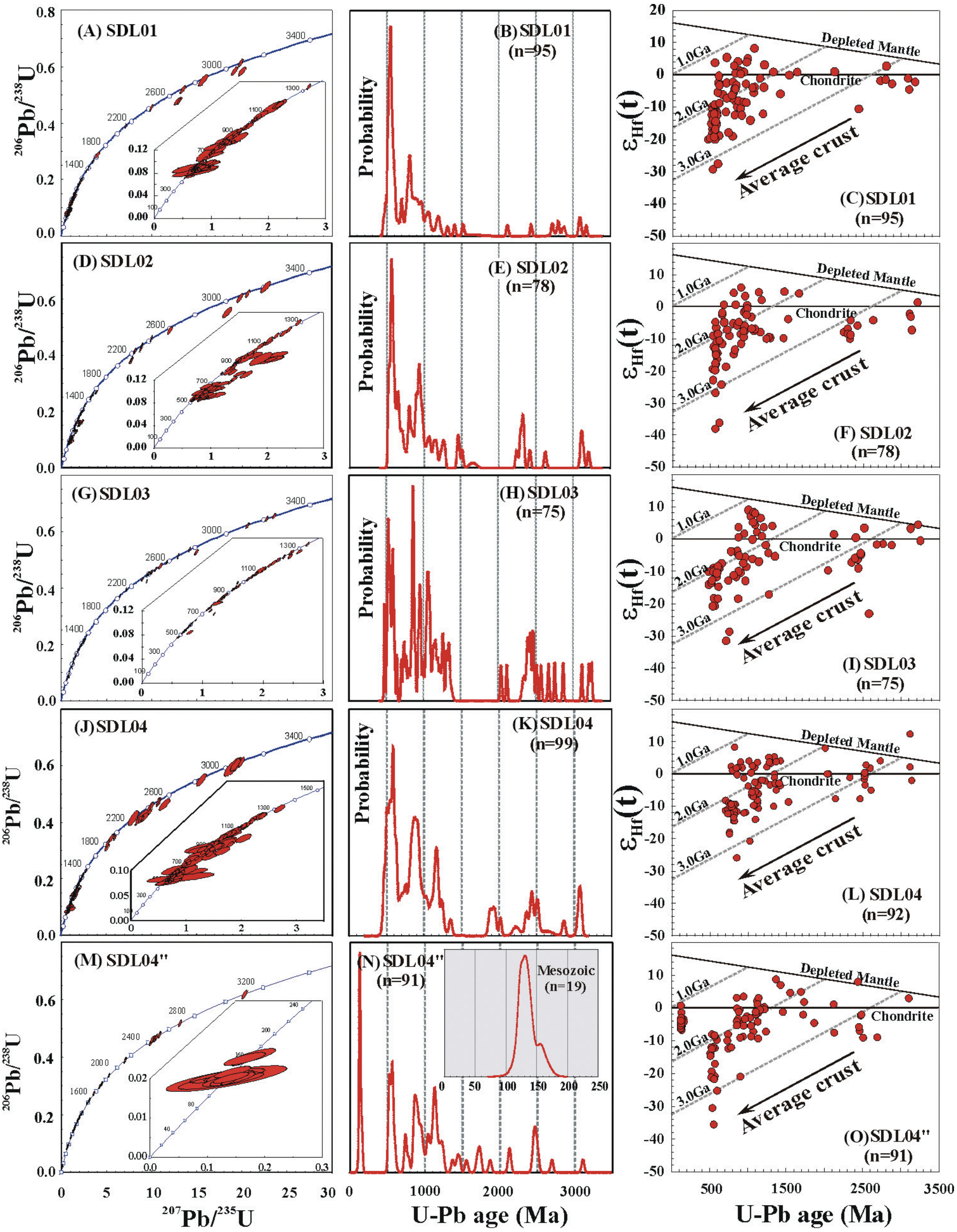

Fig. 4. U–Pb age histograms and Hf isotopic compositions of the detrital zircons from the Cretaceous Zongzhuo Formation (SDL01, 02 and 03) and Early Paleocene Sangdanlin Formation (SDL04 and 04″) in Sangdanlin. It is noted that no Mesozoic–Cenozoic zircons are identified. Regarding the zircon ages, $^{206}Pb/^{238}U$ ages are used when <1000 Ma and $^{207}Pb/^{206}Pb$ ages are used when >1000 M.

with most of them being positive in $\varepsilon_{Hf}(t)$ value (figs. 5A-5F and 5M-5U), similar to the Gangdese Batholith (Ji and others, 2009; Chiu and others, 2009).

Zheya Formation (Eocene).—Zircons from sample SDL10 are stubby to elongate and variable in size, with an average length of ~100 μm; they show oscillatory zoning under

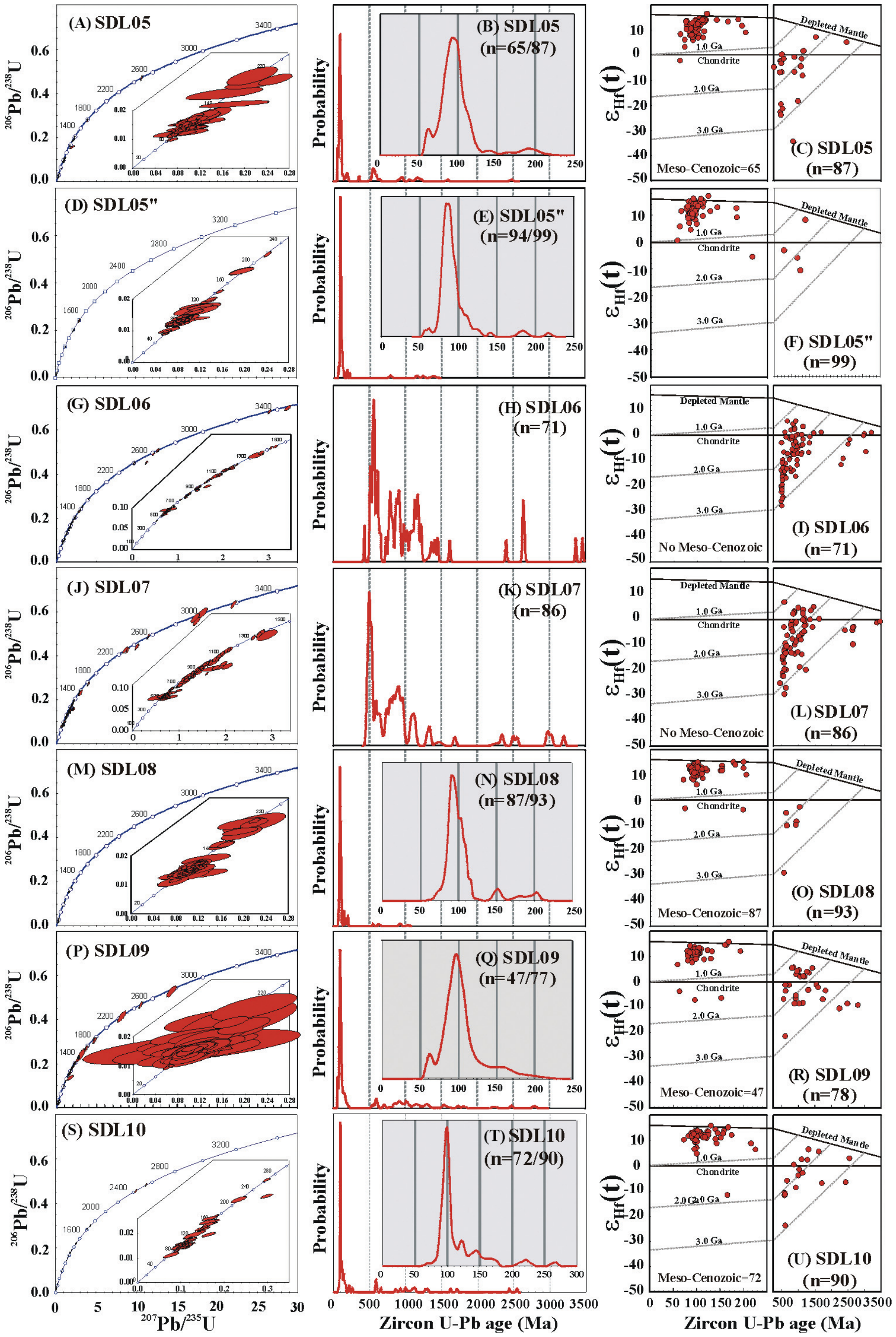

Fig. 5. U–Pb age histograms and Hf isotopic compositions of the detrital zircons from the Paleogene Sangdanlin and Zheya formations It is noted that zircons from samples of SDL06 and SDL07 are older than Mesozoic, significantly different from the remaining samples that contain abundant Mesozoic–Cenozoic zircons.

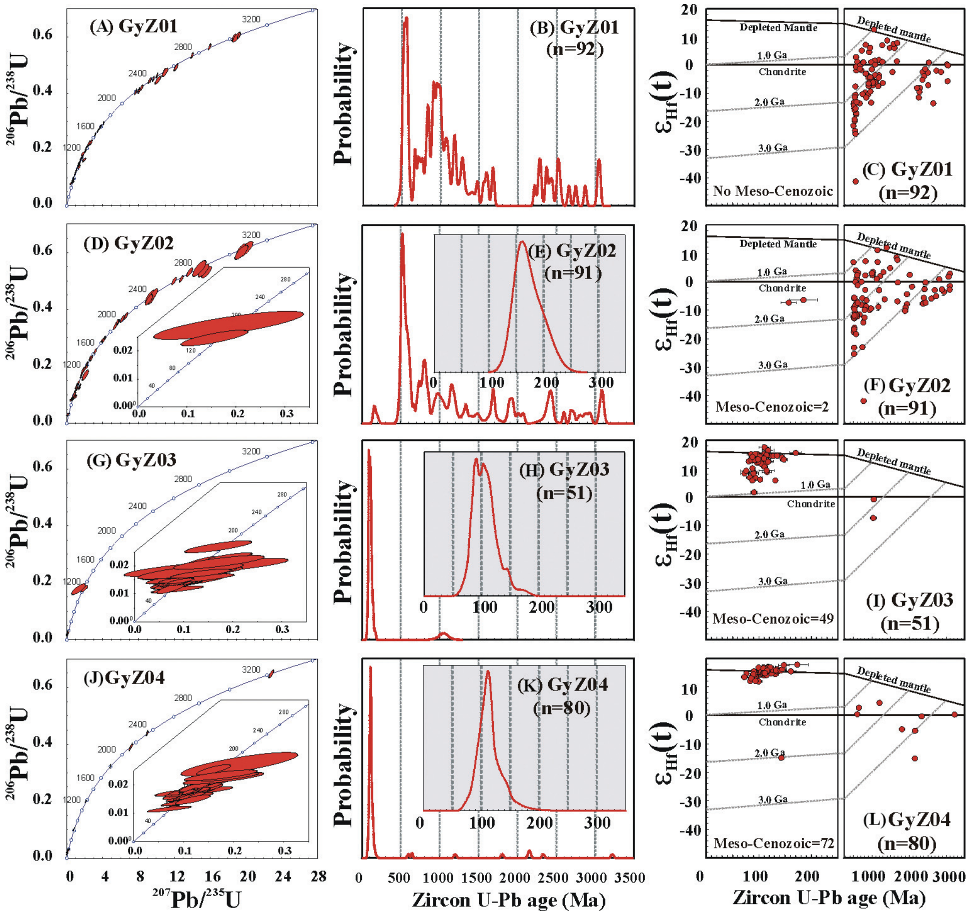

Fig. 6. Age histograms and Hf isotopic compositions of detrital zircons from the Jurassic Weimei, Early Cretaceous Gyabula and Late Cretaceous–early Paleocene Zongzhuo formations, Gyabula section, Gyangze. It is noted that the zircons from the Zongzhuo Formation are predominately of Mesozoic ages with positive ε_{Hf}(t) values.

CL. Ninety usable ^{206}Pb/^{238}U ages obtained from 100 analyses show that this sample is dominated by zircons of Mesozoic age (72 out of 90, 80%) with ages ranging from 73 ± 6 to 224 ± 5 Ma and an age peak at ~100 Ma (figs. 5P and 6Q). All these Mesozoic zircons (with one exception) display high ^{176}Hf/^{177}Hf isotopic ratios with positive, that is, relatively primitive ε_{Hf}(t) values ranging from 4.9 to 15.9 (fig. 5R).

Gybula Section, Gyangze Basin

In the Gyangze Basin sandstone was collected from the Weimei (GyZ01) and Gyabula (GyZ02) Formations. Two samples (GyZ03 and GyZ04) were collected from sandstone lenses in the Zongzhuo Formation, and six sandstones (GyZ05, GyZ06, GyZ07, GyZ08, GyZ09 and GyZ10) were taken from the overlying Jiachala Formation (fig. 3). As in the Sangdanlin Basin, the analyzed zircons are mostly rounded with grain-size of ~100 mm, and show complex internal textures. However, the zircons from the Zongzhuo Formation are mostly euhedral in shape, with grain-sizes of 100 to 300 mm and length/width ratios of ~2. Interestingly, zircons from the Jiachala

Formation are morphologically similar to those from sandstones in the Sangdanlin Basin.

Weimei and Gyabula Formations (Jurassic-Cretaceous).—Ninety-two usable U–Pb analyses from sample GyZ01 from the Weimei Formation yielded an age range from 3056 ± 16 to 497 ± 31 Ma (fig. 6A). Statistics show major age peaks at 600 to 500 and 1200 to 800 Ma with some scattered between 3.1 to 2.2 Ga (fig. 6B), with low Hf isotopic ratios and large range of ε_{Hf}(t) values from −41.8 +12.3 (fig. 6C). Zircons from the Gyabula Formation (GyZ02) show similar age patterns and Hf isotopic compositions, comparable to sample GyZ01 (fig. 6D). However, we note that this Gyabula Formation sample also contains two grains of Cretaceous zircon (fig. 6E), which have low Hf isotopic ratios with negative ε_{Hf}(t) values of −7.8 and −6.9 (fig. 6F).

Zongzhuo Formation (Cretaceous).—Zircons from the Zongzhuo Formation are more uniform in shape, internal structure and age distribution than the underlying Gyabula Formation. The two analyzed samples (GyZ03 and GyZ04) show identical age patterns and Hf isotopic compositions (figs. 6G-6L). These samples differ from the other samples in that they contain much higher percentage of Mesozoic–Cenozoic zircons. For sample GyZ03, 49 out of 51 (96%) analyses show Mesozoic U–Pb ages ranging from 73 ± 7 to 171 ± 11 Ma. For sample GyZ04, 72 out of 80 (90%) analyses show Mesozoic U–Pb ages ranging from 73 ± 6 to 173 ± 21 Ma. All except one of these zircons have high Hf isotopic ratios and positive ε_{Hf}(t) values ranging from +1.0 to +17.6, comparable to values measured from the Gangdese Batholith (figs. 6I and 6L).

Jiachala Formation (Paleocene).—Six sandstone samples (GyZ05-10) were collected from the lower part of the Jiachala Formation (fig. 3). Zircons from these samples are stubby to elongate and variable in size, with an average length of ~100 mm and mostly oscillatory zoning under CL. Grains from these samples have similar age distributions and Hf isotopic compositions (fig. 7). Samples from this formation differ from those from the underlying Zongzhuo Formation in containing high percentages of Precambrian zircons with only 25 to 35 percent of grains dating as Mesozoic–Cenozoic. Most of these young zircons display high ^{176}Hf/^{177}Hf isotopic ratios with positive ε_{Hf}(t) values (fig. 7).

Chuangde Section, Gyangze Basin

One sandstone was collected from the Gyabula (12FW64) Formation along the Chuangde section of the Gyangze Basin, and another sample (09FW156) being collected from a sandstone lens in the Zongzhuo Formation (fig. 3). As in the Gybula section, the analysed zircons from the Gyabula Formation are mostly rounded, with grain-sizes of ~100 mm, and most show complex internal textures. In contrast, zircons from the Zongzhuo Formation are mostly euhedral in shape with grain-sizes of 100 to 300 mm and length/width ratios of ~2.

Gyabula Formation (Early Cretaceous).—Ninety-five usable U–Pb analyses were obtained from sample 12FW64 from the Gybula Formation. Two analyses gave U–Pb ages of 141 ± 3 and 144 ± 5 Ma, while others yielded an age range from 3055 ± 16 to 494 ± 9 Ma, with the exception of a single grain dating at 324 ± 6 Ma (fig. 8A). Statistics have identified major age peaks at 600 to 500 and 1200 to 800 Ma, with some scatter between 3.1 to 2.2 Ga (fig. 8B).

Zongzhuo Formation (Late Cretaceous-Paleocene).—One hundred thirty-eight useable dates were derived from 140 zircon analyses from sample 09FW156. U–Pb ages range from 78 ± 3 to 2827 ± 20 Ma (fig. 8C). These zircons differ from the underlying Gybula Formation in that the Zongzhuo sandstone contains a much higher percentage (58%) of Mesozoic–Cenozoic zircons, with the main peaks at 88, 132 and 212 Ma (fig. 8D). These young zircons have high Hf isotopic ratios and positive ε_{Hf}(t) values similar to those from the Gangdese Batholith (fig. 8E). Interestingly, zircons from this sample are quite different from those from the Zongzhuo Formation (GyZ03 and GyZ04) in

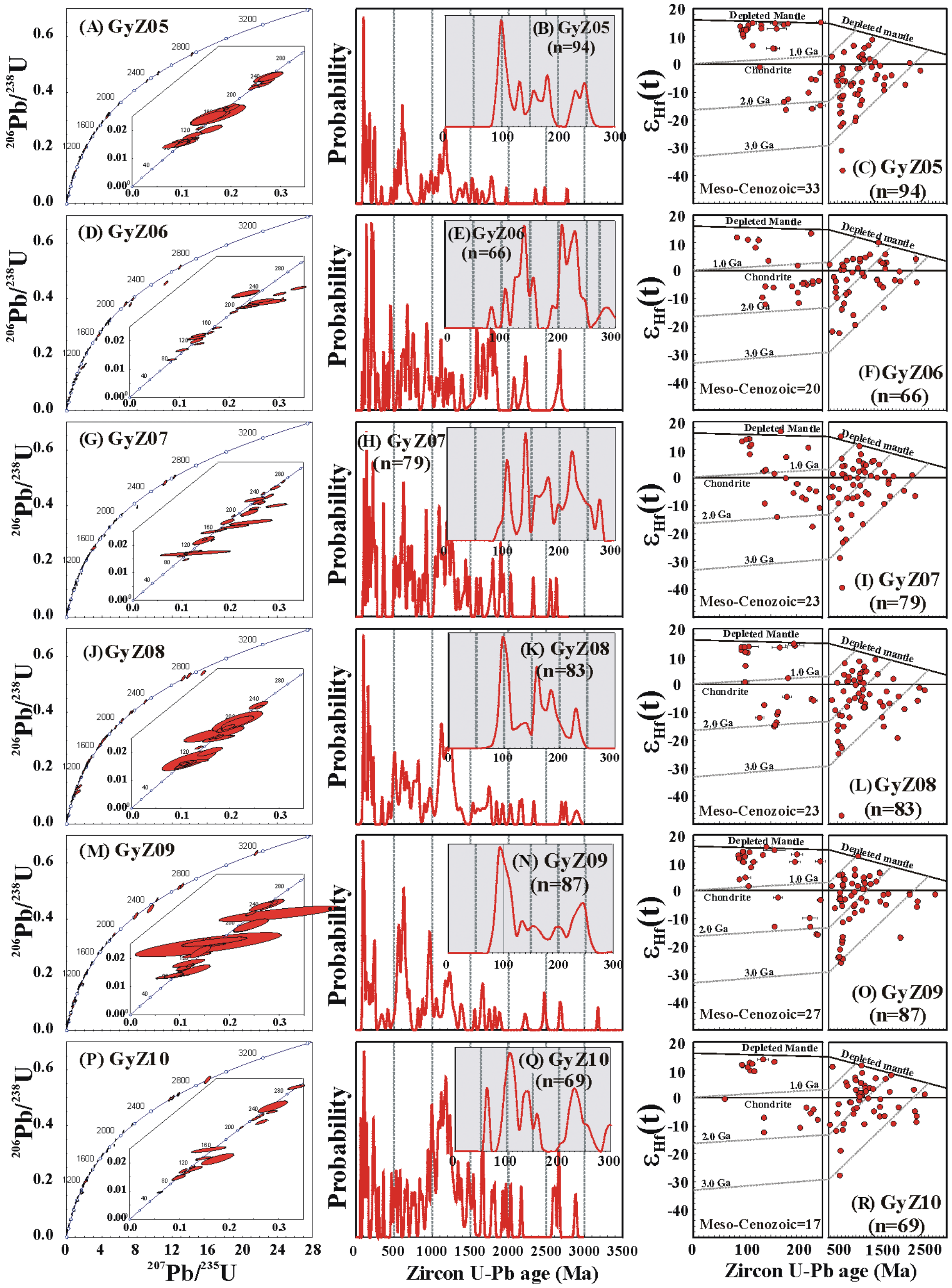

Fig. 7. Age histograms and Hf isotopic compositions of detrital zircons from the Paleocene–Eocene Jiachala Formation.

the Gybula section because the latter contains a higher proportion of Mesozoic–Cenozoic zircons (fig. 6). This indicates that the two sections have different sources. However, the zircon age pattern is similar to that of the overlying Paleocene–Eocene Jiachala Formation (fig. 7).

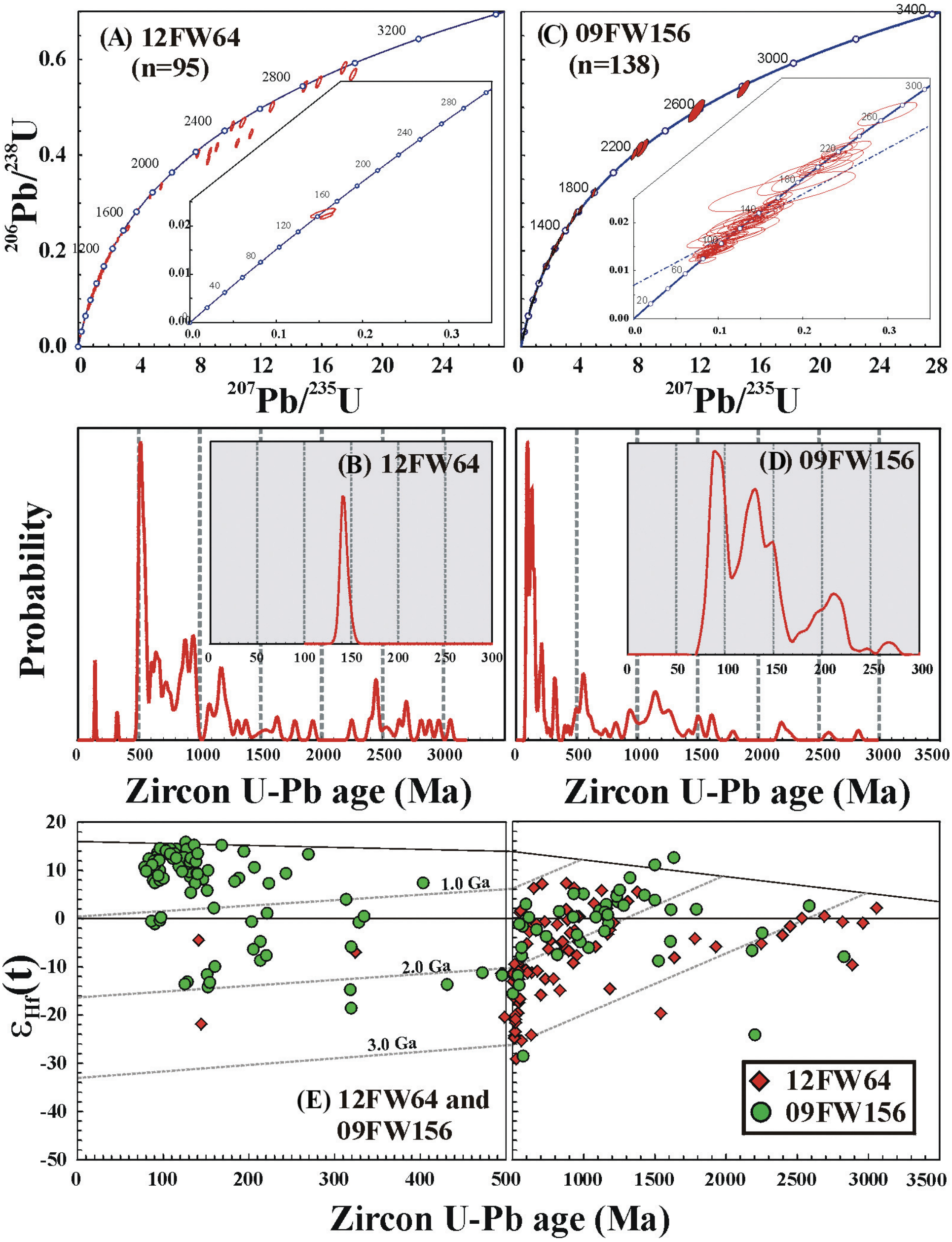

Fig. 8. Age histograms and Hf isotopic compositions of detrital zircons from the Early Cretaceous Gyabula and Late Cretaceous Early Paleocene Zongzhuo formations, the Chuangde section, Gyangze. It is noted that the zircons from the Zongzhuo Formation are predominately of Mesozoic ages with positive $\varepsilon_{Hf}(t)$ values, which are significantly different from those of the underlying Gyabula Formation.

DISCUSSION

Distinctions Between Asian and Indian Continents

The data presented above show a wide range of U–Pb ages and Hf isotopic compositions for zircons from the Sangdanlin and Gyangze basins. This range indicates that material was being derived by erosion from several different block/terranes. In order to constrain the timing of India-Asia collision using these data, we first review the differences between the Asian and Indian continents. The Lesser Himalaya is characterized by the occurrence of Archean and Paleoproterozoic zircons, while the Greater Himalaya contains Pan-African (~0.5 Ga) and Mesoproterozoic (1.2-0.8 Ga) zircons linked to granitic magmatism of that age (Parrish and Hodges, 1996; DeCelles and others, 2000; Gehrels and others, 2003; Myrow and others, 2003; Richards and others, 2005). In the Tethyan Himalaya, recent dating has identified the existences of Permian and Jurassic–Cretaceous magmatism (McDermid and others, 2002; Zhu and others, 2005b, 2009e; Xia and others, 2012; Zeng and others, 2012). Considering that the sedimentary rocks of the Tethyan Himalaya share many of the same sources as the Lesser and Greater Himalayas (Wu and others, 2007), it can be problematic to distinguish them in terms of zircon U–Pb age and Hf isotopes, although the relative abundance of different age groups does differ between the three Himalayan units. Therefore, for the purpose of this study, we will not discuss them separately, but ascribe them together as having an Indian affinity. Because the Greater Himalaya was only exposed after ~23 Ma the rocks of that range could not have been the source of the sediments considered here in any case. We conclude that the Indian continent is characterized by Precambrian age peaks (figs. 9A-9B). We also note that the limited numbers of Mesozoic zircons show low Hf isotopic ratios with negative $\varepsilon_{Hf}(t)$ values (fig. 9C).

North of the Yarlung-Zangbo suture zone, the Asian crust in Tibet consists mainly of the Lhasa Terrane, which is generally considered to have rifted from the northern margin of the Indian continent during the early Mesozoic, raising the possibility that there may be no clear difference between the Lhasa Terrane and Indian continent in rocks older than the Mesozoic. However, Zhu and others (2011b) recently argued that the Lhasa Terrane rifted from Australia and shows an age peak in detrital zircons at ~1170 Ma within Paleozoic sedimentary rocks. In contrast; the Tethyan sedimentary rocks are marked by an age population at ~950 Ma. In any case, the Lhasa Terrane is characterized by Mesozoic–Cenozoic magmatism involving emplacement of granitic rocks (Chung and others, 2005). The granites in the northern Lhasa Terrane were mostly emplaced during the Cretaceous with most ages clustering at ~120 Ma (figs. 9D-9F). Precambrian zircons show similar age and Hf isotopic features to those from the Indian continent (fig. 9E), but the Mesozoic–Cenozoic zircons mostly have negative $\varepsilon_{Hf}(t)$ values. In contrast, the Gangdese Batholith and the Linzizong volcanic rocks in the southern Lhasa Terrane were mostly formed between 208 to 8 Ma with a main peak at ~50 Ma (fig. 9D, Chiu and others, 2009; Ji and others, 2009; Zhu and others, 2011a, and references therein). In terms of Hf isotopes, zircons from the Gangdese Batholith and the Linzizong Volcanics show distinctive high Hf isotopic rations with positive $\varepsilon_{Hf}(t)$ values (figs. 9E-9F).

In summary, the Indian continent exposed south of the Yarlung-Zangbo suture is characterized by Precambrian magmatism, and no magmatic event between 118 to 40 Ma has been documented, although a minor early Cretaceous magmatism has been recorded (figs. 9A and 9C). In contrast, the Lhasa Terrane is characterized by common Mesozoic–Cenozoic magmatism. Zircons from the southern Lhasa Terrane (Gangdese arc) in particular have much higher Hf isotopic ratios and positive $\varepsilon_{Hf}(t)$ values compared to those from the Indian continent, which can be effectively used to discriminate the sources of the studied sedimentary rocks.

Age of the Indian-Asian Continental Collision in the Studied Basins

Sangdanlin area.—Before discussing the age of collision, the depositional age of the studied rocks needs to be constrained. The most widely accepted stratigraphic framework as shown by figure 3A is that the Sangdanlin Formation is Paleocene, and

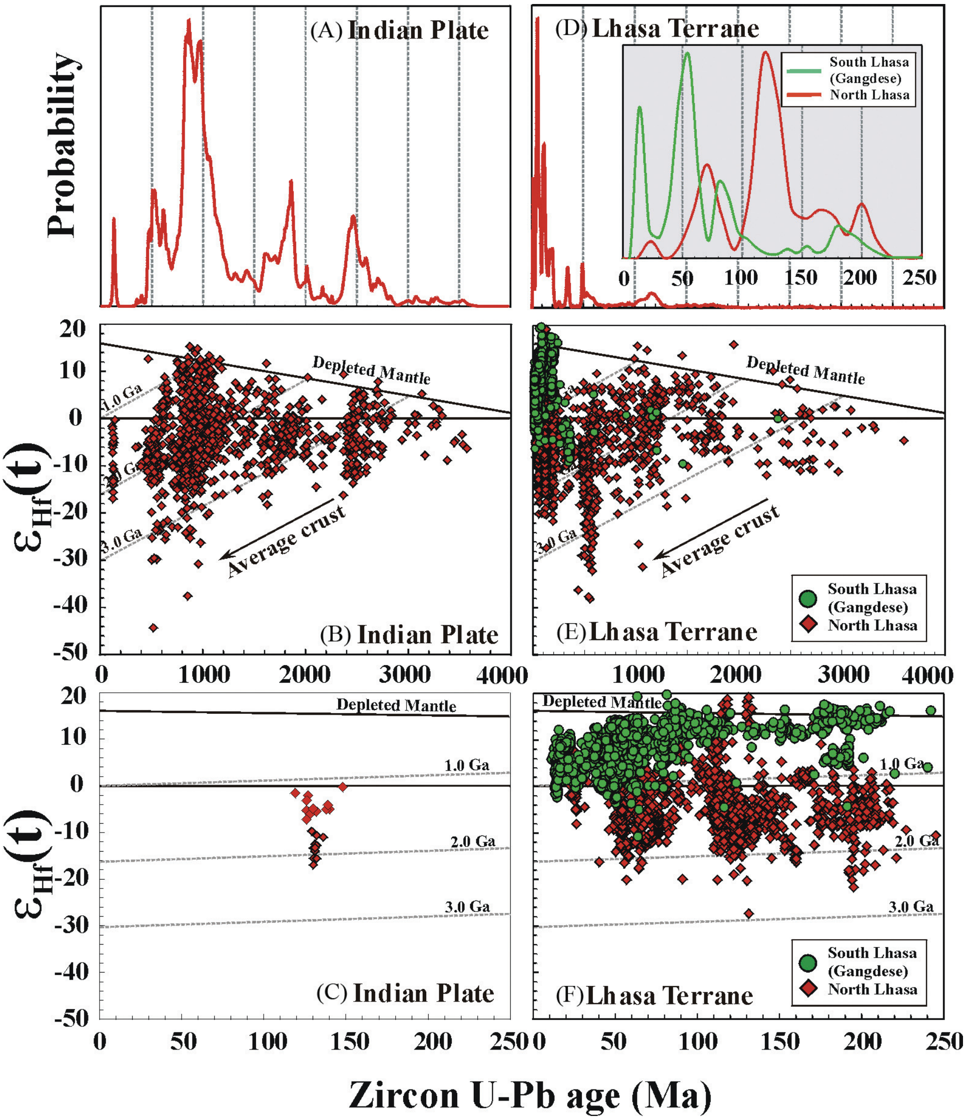

Fig. 9. Zircon U–Pb age and Hf isotopic comparisons between the Indian- and Asian-derived materials. See explanation in the text. Data sources: South Lhasa (Gangdese) (n=2287): Chu and others (2006, 2011), Chung and others (2009), Guan and others (2010, 2012), Huang and others (2010), Ji and others (2009, 2012a, 2012b), Lee and others (2007), Li and others (2011b), Xu and others (2010), Yang and others (2011), Zhang and others (2007a), Zhu and others (2009c, 2011a). North Lhasa (n=2937): Chen and others (2010b), Chiu and others (2009), Chu and others (2006, 2011), Guo and others (2011, 2012), Huang and others (2012), Jiang and others (2010, 2012), Liang and others (2008), Liu and others (2010), Meng and others (2010), Qi and others (2011), Wang and others (2012b), Xu and others (2012), Zhang and others (2007b, 2008, 2010a, 2010b, 2012c), Zhao and others (2011), Zheng and others (2012), Zhou and others (2008), Zhu and others (2009a, 2009b, 2009d, 2011a, 2011b, 2012). Indian Plate (n=1178): Chu and others (2011), Hu and others (2010), Kemp and others (2009), Ravikant and others (2011), Richards and others (2005), Spencer and others (2012), Sun and Hu (2012), Xia and others (2012), Zhu and others (2011b).

the overlying Zheya Formation is Eocene. This conclusion was based on the radiolarian fauna from interlayered cherts (Ding and others, 2005). However, Li and others (2007) identified some Eocene radiolarian fauna from cherts in the middle part of the

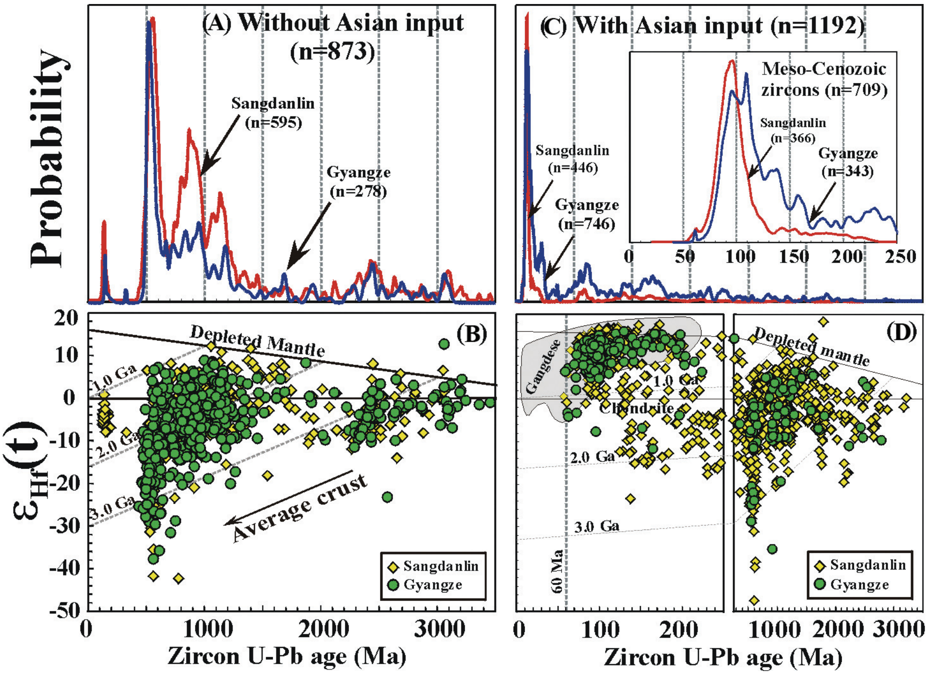

Fig. 10. Comparison of detrital zircon U–Pb ages and Hf isotopes between the Sangdanlin and Gyangze basins. The Gangdese field is from figure 9.

Sangdanlin Formation [unit 16 of Li and others (2007)]. As a result, these authors concluded that the Sangdanlin Formation was deposited during the early Eocene, and not Paleocene as suggested by Ding and others (2005). We are not experts on radiolaria, and hence have no experience to judge between the competing biostratigraphic data. However, the Ding and others (2005) model is supported by the investigation of Chan (ms, 2006) and so we apply this stratigraphic subdivision to this study.

Initial continental collision means the end of oceanic subduction and direct contact between continental blocks with the possibility of material exchange between them. For the twelve samples collected from the Sangdanlin Basin that are deposited on the Indian continent, these can be divided into two groups based on the character of the Mesozoic–Cenozoic zircons. The first group includes samples SDL01, 02, 03, 04, 04″, 06 and 07, which have similar U–Pb age patterns and Hf isotopic compositions (figs. 4 and 5). When these data are compiled together, they show two age peaks at ~550 and 850 Ma, respectively, and have similar Hf isotopic composition to other rocks from the Tethyan Himalaya (figs. 9B and 10B). The second group of samples (SDL05, 05″, 08, 09 and 10) are characterized by the occurrence of Mesozoic–Cenozoic (224-57 Ma) zircons, but with minor populations dating from the Early Paleozoic–Neoproterozoic (659-529 Ma) and Mid-Proterozoic (1308-803 Ma) (fig. 10C). We also show that these Mesozoic–Cenozoic zircons have identical Hf isotopic compositions compared to those from the Gangdese Batholith (figs. 9E-9F and 10D), consistent with derivation from the Asian continent. Among these samples with Asian input, SDL05 and 05″ were collected from within radiolarian zone RP4 (63-61 Ma, fig. 4A), with the youngest zircons dating at 62 ± 1 and 57 ± 2 Ma, respectively. Therefore, it is reasonable to conclude that initial collision between India and Asia in the Saga area occurred at ~60 Ma, considering the analytical uncertainties.

Wang and others (2011) have identified a younger group of ~54 Ma zircons from the Sangdanlin area that would argue for younger sedimentation and collision. However, these grains are part of a population with a peak age of ~60 Ma (Wang and others, 2011, fig. 7), comparable to our data in this study. In addition, the sample studied by Wang and others (2011) was taken from a bed stratigraphically higher than our samples SDL05 and SDL05″. On the basis of the present age control we favor the first arrival of Asian material on the Indian continental margin at ~60 Ma, although future refinement of the age model might indicate collision even younger than 54 Ma.

Gyangze area.—In the Gyangze Basin, the zircons from the Weimei and Gyabula Formations show similar U–Pb age patterns and Hf isotopic compositions compared to those from the older group of samples from the Sangdanlin Basin (figs. 10A and 10B). Compared to the Tethyan sedimentary rocks (figs. 10A-10B), the only difference is that the sedimentary rocks in the Gyangze Basin contain far fewer zircons that date ~1000 Ma, but instead have more ~500 Ma zircons. In sandstone from the Gyabula Formation, four grains show Cretaceous ages with negative $\varepsilon_{\mathrm{Hf}}(\mathrm{t})$ values (fig. 10B). However, the overlying Upper Cretaceous Zongzhuo Formation sedimentary rocks show characteristic Mesozoic zircons with positive $\varepsilon_{\mathrm{Hf}}(\mathrm{t})$ values, which is identical to those from the Gangdese Batholith (fig. 10D). We thus conclude that material exchange between India and Asia took place during sedimentation of the Zongzhuo Formation.

However, presently the depositional age of the Zongzhuo Formation is debatable. Some researchers have proposed that this formation could be deposited as late as the Eocene (<55 Ma) (Burg and Chen, 1984; Searle and others, 1987; Liu and Aitchison, 2002), but no details have yet been published concerning the radiolarian assemblages that support this model. Liu and Aitchison (2002) provided some details about Eocene radiolaria, but their identification of such young radiolarians has not been verified by later investigations at the same locality (Cai and others, 2011). In contrast, detailed study of the mud matrix of the Zongzhuo Formation from numerous locations has identified the presence of a Maastrichtian radiolarian fauna (Wu and Li, 1982; Wan and others, 2005; Li and others, 2009a, 2009b, 2011a). Therefore, we might favor sedimentation of the Zongzhuo Formation in the Maastrichtian stage (65-70 Ma), which would require initial collision between India and Asia to have occurred prior to 65 Ma. As in the Sangdanlin area, however, collision would be Eocene if the depositional age of the Zongzhuo Formation was revised to Eocene.

Cai and others (2011) also found an abrupt change of source material between the Gybula and overlying Zongzhuo Formations based on petrographic, detrital zircon U–Pb ages and Lu–Hf isotopes, as well as whole-rock Nd isotopes, and spinel compositional data. These authors further proposed that the initial collision between India and Asia occurred at ~70 to 65 Ma. However, Sun and others (2011) identified Paleocene (61-64 Ma) detrital zircons in the Zongzhuo Formation at Beisha (~20 km southwest of the Chuangde section), and from the Zongzhuo Foramation in the studied Chuangde section (Hu, personal communication). If this is true then the Zongzhuo Formation might be deposited in the Paleocene or even Eocene.

The Gyangze Basin lies close to the Gangdese Arc, which shows continuous magmatism during the period of 65 to 41 Ma (Ji and others, 2009). As a result, the youngest zircon age can be considered to approximate the depositional time (Dickinson and Gehrels, 2009). Consequently, we favor sedimentation of the Zongzhuo Formation at ~60 Ma, although an older (or younger) initiation of deposition is not excluded because no zircon younger than 65 Ma has been found in our samples (figs. 6 and 8). We currently favor India and Asia collision starting at ~60 Ma in the Gyangze Basin. This conclusion is also supported by the recent work of Hu and others (2012), who proposed an initial collision age of ~62 Ma based on stratigraphic, sedimentological and subsidence data from these Cretaceous–Palaeogene strata.

Recently, the first arrival of Asian material on the Indian continent in Gamba (located to the south of the studied Gyangze Basin) was dated at ~55 to 50 Ma, which was interpreted as the collisional age of India and Asia (Najman and others, 2010; Zhang and others, 2012b). Considering that our studied sections are located closer to the suture than these sections, the older age we favor here is logical because of time that would be needed for the foreland basin to propagate this distance after initial collision.

Diachroneity of the Initial Collisional Age

We conclude that the initial collision between India and Asia took place at ~60 Ma in southern Tibet, based on our favored biostratigraphy. In contrast, Rowley (1996, 1998) used stratigraphic data from the Tethyan Himalaya to propose a diachronous collision initiating in the late Ypresian (≲52 Ma) in the west and progressing into the Lutetian (~45 Ma) in the east. However, Ding and others (2005) proposed that India and Asia collided first in southern Tibet, followed by suturing progressing both westward and eastward, while Najman and others (2005) argue that there is no evidence of diachroneity in collision along strike.

Collision in the northwest Himalaya (around Nanga Parbat) appears to have involved a complex interaction between the Indian and Asian plates, the Spontang ophiolite and an intra-oceanic (Ladakh-Kohistan) arc between them (Yin and Harrison, 2000; Burg, 2011). Most studies propose that the Ladakh-Kohistan arc collided with Asia along the Shyok suture during the Cretaceous, and then the composite plate collided with India along the southern Indus-Yarlung Suture Zone at ~55 to 50 Ma (Beck and others, 1995; Rowley, 1996; Rehman and others, 2011). More recently others have suggested that the arc collided with India first at ~50 Ma or even ~80 Ma, followed by India-arc collision with Asia at ~40 Ma (Khan and others, 2009; Bouilhol and others, 2013; Chatterjee and others, 2013). Stratigraphic data favor closure of the Indus-Yarlung Suture starting in the Late Ypresian (~50 Ma) (Rowley, 1996, 1998; Najman, 2006; Green and others, 2008), which is also consistent with dating of detrital zircons from sandstones in the suture zone (Wu and others, 2007; Henderson and others, 2010b, 2011). Furthermore, in Ladakh in the western Himalaya, metamorphism of the subducted leading edge of the Indian continent (Tso Morari eclogite) took at place at ~45 to 53 Ma (Leech and others, 2005, 2007). New dates from this eclogite indicate that the passive margin of India experienced collision after 51 Ma in this area, followed by peak metamorphism at ~47 to 43 Ma (Donaldson and others, 2013). Further northwestward in the Pakistan Himalaya, the Kaghan eclogite has been extensively studied in terms of geochronology (de Sigoyer and others, 2000; Kaneko and others, 2003; Parrish and others, 2006; Wilke and others, 2010), with data implying subduction of the Indian continent to a depth of >100 km before 46 Ma. India-Asia collision in the NW Himalaya is relatively well constrained at ~50 Ma.

Further west in the Waziristan area in northwest Pakistan, Beck and others (1995, 1996) proposed that the India-Asia collision took place as early as 66 to 55 Ma, based on obduction/thursting of an accretionary complex over the Indian passive continental margin at 66 Ma. This accretionary complex was originally developed at the leading edge of the Asian plate, but was subsequently covered by Paleocene-Eocene limestone with an unconformity no later than 55 Ma. However, Rowley (1996) argued that the thrusting could be related to an intra-oceanic obduction event rather than contact of the Asian continent with India, and that the India-Asia collision in that region took place simultaneously to that in the NW Himalaya at ~50 to 51 Ma, consistent with the data from nearby Ladakh.

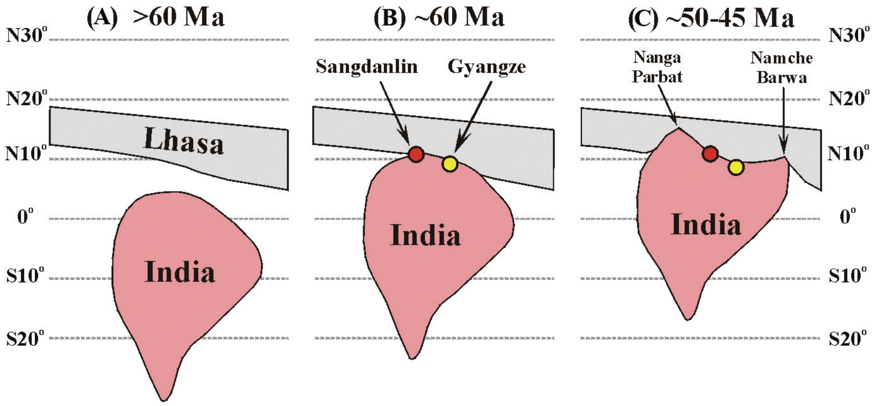

Fig. 11. Schematic evolution of the collision between India and Asian during 70–45 Ma. The latitude of the Lhasa terrane is from Chen and others (2010a).

In eastern Tibet, the time of collision is not well constrained because of the lack of preserved sedimentary rocks. In terms of zircon U–Pb geochronology, Ding and others (2001) identified an ~40 Ma metamorphic event from the high-pressure granulite rocks in Namche Barwa, within the eastern syntaxis of the Himalaya. Recently, Zhang and others (2010c) argued for a slightly younger high-pressure metamorphic age of 37 to 32 Ma. These ages are ~5 to 10 m.y. younger than those of the eclogite in northwest Himalaya, and suggested that the collision in the east probably took place prior to ~45 to 40 Ma. Further southward, the Indo-Burman Range ophiolite, located along the India and Myanmar boundary, which represents the southern continuation of the Indus–Yarlung-Zangbo ophiolitic complexes is believed to have formed during Late Jurassic to Early Eocene. These units suggest a collision event between India and Burma block around the Middle Eocene (~40 Ma, Acharyya, 2007; Chatterjee and Ghose, 2010; Ghose and others, 2010; Bannert and others, 2011; Baxter and others, 2011).

As noted in the introduction, the initial age of collision between India and Asia has been constrained using multiple techniques. In this study, the initial collision of India and Asia is defined as the time of disappearance of the oceanic lithosphere and first contact between continental crust blocks. This collision pre-dates the final elimination of seawater from the suture zone. After initial collision, rocks from one continent may be uplifted, eroded and transported into the sedimentary basins overlying the other continental block. In Ladakh rapid cooling of the Ladakh Batholith after 50 Ma suggests that it was the Asian margin that experienced the first phase of rapid uplift (Clift and others, 2001). Furthermore, after collision, the Indian continent must have been subducted beneath the Asian continent. Therefore, we favor a model in which India-Asia collision initially took place in southern Tibet at ~60 Ma, and then become younger to the west and east separately (fig. 11). The final collision is dated at ~50 and 45 Ma in northwestern and eastern Himalaya. This conclusion is quite different from the view that suturing became younger eastward following initial collision at 50 Ma in the NW Himalaya and final suturing at ~45 Ma in eastern Tibet (Rowley, 1996, 1998) or was effectively synchronous along strike (Najman and others, 2005).

Any Arc-Continent Collision in Tibet During the Cenozoic?

We argue here that the Mesozoic–Cenozoic detrital zircons found in sandstone in the Tethyan Himalaya that have positive $\varepsilon_{Hf}(t)$ values were derived from Asia. However,

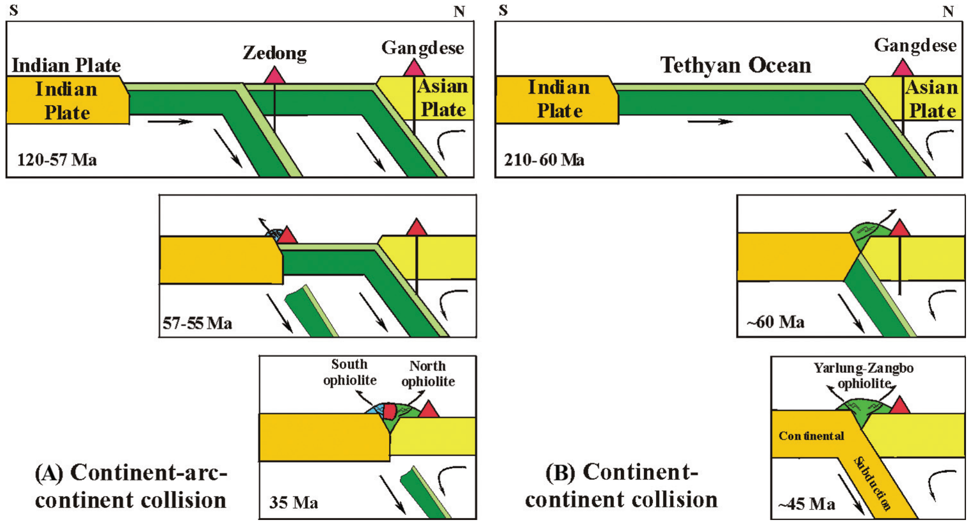

Fig. 12. Cartoons showing the collisional process between India and Asia with (A) or without (B) an intraoceanic arc [modified from Ali and Aitchison (2008)].

Aitchison and others (2007) attributed such grains to an intraoceanic arc and ophiolite within the Neotethyan ocean. These workers proposed that India first collided with the intraoceanic arc (Zedong) at ~55 Ma, with subsequent final continental collision at ~35 Ma (fig. 12A), similar to the Cretaceous obduction of Spotang ophiolite and arc in Indian Ladakh at 65 to 67 Ma (Pedersen and others, 2001). This conclusion was built on several lines of evidence. Based on paleogeographic reconstruction, Aitchison and others (2007) placed the Lhasa Terrane at around N30° at ~55 Ma. They proposed, therefore, that India and Asia were too far apart to have collided at 55 Ma. However, their paleomagnetic reconstruction is not supported by the recent data that suggests that the Lhasa Terrane was at an appropriately constant latitude from late Cretaceous to early Paleogene with a paleo-latitude of ~N5 to 10° (Chen and others, 2010a; Dupont-Nivet and others, 2010; Liebke and others, 2010; Sun and others, 2010, 2012), comparable to that of the Tethyan sediment at 55 Ma (Patzelt and others, 1996; Najman and others, 2010; Yi and others, 2011). The exceptions are data reported by Tan and others (2010) and Meng and others (2012) who attributed a paleoaltitude of ~N21 to 27° for the Lhasa Terrane during the Paleocene and proposed a collisional age of 43 to 50 Ma. However, this result might represent a short-term event potentially leading to a snapshot record of the Earth magnetic field at high inclination (Najman and others, 2010).

Another argument Aitchison and others (2007) advocated to support late collision is the timing of the cessation of marine and the beginning of fluvial sedimentation along the suture zone. Evidently, these can only yield a minimum, but not an initial age of collision. Additionally, they argued that the Eocene Liuqu Conglomerate, which is a continental deposit laid down after collision of India and the intraoceanic arc, contains no Asian but instead Indian and ophiolitic materials (Davis and others, 2002). It is therefore crucial to know whether the Liuqu Conglomerate was derived from the erosion of an intraoceanic arc. Ar–Ar and U–Pb isotopic dating have demonstrated that the volcanic and granitic rocks in the Zedong Terrane/Ophiolite were formed during the Late–Middle Jurassic, with ages ranging from 152 to 163 Ma (McDermid and others, 2002). However, recent U–Pb dating of the detrital zircons from the Liuqu

Conglomerate identified a predominant population of Early Cretaceous zircon, with very minor Jurassic zircon (Wang and others, 2010). Therefore, the Liuqu Conglomerate could not have been eroded only from rocks of the same age as the preserved fragments of the Zedong intraoceanic arc. Combined with Hf isotopic data and the lack of granitic and volcanic pebbles, Wang and others (2010) proposed that this conglomerate was mostly a product of recycling from Xigaze forearc sedimentary rocks, that is, was derived from the Asian margin.

The Mesozoic–Cenozoic zircons identified in this study from the Sangdanlin and Gyangze basins are mostly Early Cretaceous (fig. 10C), not Jurassic as might be expected if there had been a collision between India and a Zedong arc. However, these Cretaceous zircons are frequently identified at the leading edge of the Asian plate, in such potential sources as the Gangdese arc and the Xigaze forearc basin (Ji and others, 2009; Wu and others, 2010), indicating that these materials are likely Asian-derived. We do however recognize that such grains could be sourced from within the Indian plate, because volcanic rocks and hypabyssal dikes have been observed within the Tethyan Himalaya in central Tibet (Zhu and others, 2005b; Wan and others, 2011; Liu and others, 2013). Nonetheless, the Cretaceous zircons from the Sangdanlin Basin also correlate well with the Gangdese arc, as do those from the Zongzhuo Formation in the Gyangze Basin. However, the Jiachala Formation contains more contribution from the northern Lhasa Terrane or Tethyan Himalaya (fig. 7). Whatever, the source of the recycled zircons for the Liuqu Conglomerate strongly argues that no arc collision took place in southern Tibet, and the Asian-derived material was deposited on the passive continental margin of the Indian plate during sedimentation of the Sangdanlin and Zongzhuo formations, tentatively dated as Paleocene and Upper Cretaceous–Paleocene respectively (fig. 12B).

It is beyond the scope of this work to discuss whether the Zedong Terrane is a tectonic slice of the continental Gangdese arc or an independent intraoceanic arc. During the Jurassic igneous activity was widespread in the Gangdese, north to the Yarlung-Zangbo suture zone. The Zedong arc is now too small to affect the collision compared with the huge Indian and Asian continents, although the degree to which the arc has been eroded is less well known, much like the Spontang Ophiolite and Spong Arc of the NW Indian Tethyan Himalaya (Pedersen and others, 2001). At present, we do not support the idea of an arc-continent collision between India and a Zedong Arc before India and Asia amalgamation.

Recently, another similar model, based on paleomagnetic data, suggested that a micro-continent, now preserved as the Tethyan Himalayan collided with Asia firstly at ~50 Ma, followed by the rest of India colliding with the composite Asian plate at ~25 to 20 Ma. This model requires oceanic subduction along a suture zone at the location of the Greater Himalaya (van Hinsbergen and others, 2012), and is similar to that of Liu and others (2012) who proposed that the Yarlung-Zangbo Suture represents the back-arc basin to a Neotethyan Ocean located within the Greater Himalaya. Until identification of any subduction/suturing signature within the Greater and Tethyan Himalayas to the south of the Yarlung-Zangbo Suture Zone we consider that this model is unlikely.

CONCLUSIONS

A comprehensive dataset of U–Pb and Hf isotopic analyses for detrital zircons from clastic sedimentary rocks in southern Tibet leads to the following conclusion:

(1) In western Tibet, Cretaceous sedimentary rocks from the Sangdanlin Basin received material eroded from the Indian continent, but that material from Asian rocks probably derived from the Gangdese Arc that had started to reach the Indian continental margin by ~60 Ma, based on existing biostratigraphy. This age can be considered as the minimum age of the Indian-Asian collision

in the area. Alternative age models raise the possibility of an Eocene collision (<54 Ma) but are currently not favored;

(2) In the Gyangze Basin of central Tibet, sedimentary rocks deposited prior to the Maastrichtian (71-66 Ma) are solely Indian-derived. However, the Maastrichtian-Paleocene Zongzhuo Formation is mostly Asia-derived, suggesting that the Indian-Asian continental collision in the area started also at ~60 Ma. Again, controversies over the age control leave open the possibility of an Eocene collision but this seems less likely;

(3) The onset of India-Asia collision is broadly constrained at ~45 Ma in southeastern Tibet and ~50 Ma in western Himalaya. Therefore, the first contact between India and Asia probably took place initially in the central part of the suture (~60 Ma), and the suturing propagated westward (~50 Ma in northwest Himalaya) and eastward (~45 Ma in southeastern Himalaya and Indo-Burman Range).

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Appendix I

http://earth.geology.yale.edu/~ajs/SupplementaryData/2014/01Wu.xlsx

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