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Provenance analysis of upper Cretaceous strata in the Tethys Himalaya, southern Tibet: Implications for timing of India–Asia collision

Fulong Cai, Lin Ding ⁎, Yahui Yue

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| Keywords: Tethys Himalaya provenance analysis detrital zircons Cr–spinel Nd-isotopes initial collision | most likely derived from the Indian continent. Overlying conformably is the Santonian–Maastrichtian Chuangde Formation, which consists of red shale, limestone and chert. The Chuangde Formation is in turn overlain by the late Maastrichtian–late Paleocene Zongzhuo Formation, which is composed of black mudstone and lithic sandstone enclosing various olistoliths of sandstone, limestone and chert. The Rilang conglomerate is a lens which is located within the upper part of the Zongzhuo Formation and consists of an upward-thinning and fining succession of volcanic conglomerate, sandstone and black mudstone. The Zongzhuo Formation and the Rilang conglomerate record an abrupt influx of Cretaceous zircon grains with juvenile Hf isotopic compositions, arc-related Cr–spinels and positive εNd(0) sediments, suggesting an arc and suture-zone provenance. The change in provenance of upper Cretaceous strata from the southern Indian continent to a northern arc and suture zone is attributed to either (1) initial collision between the Indian plate and Lhasa terrane, or (2) initial collision between the Indian plate and an intra-oceanic arc. We prefer option (1) that the initiation of India–Asia collision occurred during Maastrichtian (~70–65 Ma).  © 2011 Elsevier B.V. All rights reserved. |

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| Article history:  Received 12 November 2010  Received in revised form 28 February 2011  Accepted 28 February 2011  Editor: T.M. Harrison | The provenance of upper Cretaceous strata in the Tethys Himalaya provides critical constraints on the closure time of the Neo-Tethys Ocean and the initial India–Asia collision. This paper reports detailed petrographic studies, in-situ detrital zircon U–Pb ages and Lu–Hf isotopic analyses, whole rock Nd-isotopes, and Cr–spinel electronic microprobe data from upper Cretaceous clastic sedimentary rocks of the Tethys Himalaya near Gyangze, southern Tibet. The Berriasian–Coniacian Jiabula Formation consists of black mudstone, chert and minor quartz arenite, and is dominated by detrital zircons with Archean–Cambrian U–Pb ages which were |

# 1. Introduction

Knowledge of the initiation age of India–Asia collision is critical for understanding the early history of the Himalaya orogenic belt and providing constraints on models for the growth of the Himalaya–Tibetan orogen. Despite this importance, processes of the initial India–Asia collision in southern Tibet remain poorly known relative to that in the northwestern Himalaya. Two proposed models to explain how India–Asia collision occurred in southern Tibet are single stage collision and multistage collision respectively. The single stage collision suggests that no intra-oceanicsubductionsystemexisted. However, the initiation age of India–Asia collision is controversial and ranges from the latest Cretaceous (Willems et al., 1996; Yin and Harrison, 2000) to the middle Eocene (Burg etal.,1987;Dingetal.,2005;Searleetal.,1987,Zhuetal.,2005a).Recently, Aitchison's group proposed an alternative multistage collision model that intra-oceanic arc collision and ophiolite obduction with Indian plate occurredduringearlyCenozoicfollowedbyultimatelyIndia–Asiacollision at Eocene/Oligocene boundary (Aitchison, 2000; Aitchison and Davis,

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| ⁎ Corresponding author. Tel.: +86 10 62849679. E-mail address: dinglin@itpcas.ac.cn (L. Ding).  0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.  doi:[10.1016/j.epsl.2011.02.055](http://dx.doi.org/10.1016/j.epsl.2011.02.055) |

2004;Aitchisonetal.,2007a;Davisetal.,2002).ThisalternativeIndia–Asia collision model requires that the southernmost margin of Lhasa terrane retained its approximate present position at ~30°N deduced from Apparent Polar Wander Path of the stable Eurasian plate (Ali and Aitchison, 2004, 2006). That is in conflict with recent paleomagnetic results from the Paleocene–Eocene Linzizong Group and dykes indicating thatsouthernmostmarginresidedatlowlatitudes of~10°N–~20°N(Chen et al., 2010; Dupont-Nivet et al., 2010; Liebke et al., 2010). Thus, a later collision at ~35 Ma as suggested by Aitchison et al. (2007a) may be impossible (Chen et al., 2010; Najman et al., 2010). However, paleomagnetic data cannot deny the former existence of an intra-oceanic arc.

Provenance analysis of clastic rocks is an effective approach to constrain the initiation age of India–Asia collision by the first arrival of Asia-derived detritus on the Indian passive continental margin (Najman, 2006; Yin, 2006). TheTethys Himalaya located on the downgoing plate as the Indian continent was subducted northward beneath the Lhasa terrane contains significant information about the closure time of the Neo-Tethys Ocean and the initiation age of India–Asia collision. Provenance studies on Eocene strata of the Tethys Himalaya indicated the presence of detritus from the Asian plate suggesting that India–Asia collision had occurred by this time (Ding et al., 2005; Zhu et al., 2005a). Rapid changes in sedimentation patterns (Willems et al., 1996) and tectonic subsidence (Rowley, 1998), along with the influx of accretionary prism and trench materials have been found in late Masstrichtian strata in southernTibet (Tingri and Gyangze) and have been attributed to initial India–Asia collision (Liu and Einsele, 1996; Willems et al., 1996; Yin and Harrison, 2000). However, the lack of evidence for unambiguously Asiaderived detritus in the upper Cretaceous strata of the Tethys Himalaya questioned this early age for collision in southern Tibet.

In this paper, we carried out a detailed provenance study on the upper Cretaceous clastic sedimentary rocks of the northern Tethys Himalaya, near Gyangze, southern Tibet and present new detrital zircons U–Pb–Hf isotopic, Cr–spinel electronic microprobe, bulk rock Nd-isotopic, and modal sandstone petrographic data. We do this to present when Asia-derived detritus deposited first onto the Indian passivecontinental margin.Ourresults showthat provenancedrastically changed during the deposition of the Santonian–Maastrichtian Chuangde Formation, providing new implications for the initial India– Asia collision.

# 2. Geological setting

The study area is located in south–central Tibet, which consists from north to south of the Lhasa terrane, Yarlung Zangbo suture zone, and the Tethys Himalaya (Fig. 1). The geology of each of these units is summarized in the following.

The Lhasa terrane was contiguous with Gondwanaland during the Paleozoic (Dewey et al., 1988; Yin et al., 2010). The basement in the few places where it is exposed is mid-Proterozoic to early Cambrian in age (Dewey et al., 1988; Guynn et al., 2006; Harris et al., 1988), and the cover consists mainly of upper Paleozoic to Tertiary sedimentary and volcanogenic strata (Yin and Harrison, 2000 and references therein). The dominant magmatic event occurred in the southern part of the Lhasa terraneandisreferredtoastheGangdesearc.TheGangdesearccomprises Cretaceous to early Tertiary calc-alkaline granitoids (Debon et al., 1986) and 68–43 Ma nonmarine volcanic sequences of the Linzizong Group (He et al., 2007) which are traditionally attributed to northward subduction of Neo-Tethys oceanic lithosphere beneath the southern Lhasa continental margin (Allegre et al., 1984 Tapponnier et al., 1981), but may at least in part be associated with early subduction of the Tethys Himalaya continental lithosphere beneath the southern margin of the Asia plate (Mo et al., 2007). Moreover, recent work suggested that arc magmatism initiated as early as Jurassic time (Chu et al., 2006). The Linzizong Group is weakly deformed and lies on strongly shortened (N50%) Cretaceous and older strata (Allegre et al., 1984; Burg and Chen, 1984; Kapp et al., 2007; Murphy et al. 1997; Tapponnier et al., 1981). The Gangdese forearc basin exposed along the southern margin of the Lhasa terrane includes Albian– Ypresian marine sediments (Ding et al., 2005; Wan et al., 1997) that were mainly derived from the Gangdese arc (Dürr, 1996; Wu et al., 2010).

The Yarlung Zangbo suture zone represents remnants of an oceanic basin between the India and Lhasa terranes that closed by northward subduction beneath the Lhasa terrane and possibly one or more oceanic island arc terranes. It consists of late Jurassic to early Cretaceous opholitic rocks of back-arc and intra-oceanic arc affinities (Bedard et al., 2009; Dubois-Côté et al., 2005; Gopel et al., 1984; Malpas et al., 2003; Miller et al., 2003), associated accretionary prism rocks (Wang et al., 1999), late Jurassic to early Cretaceous island arc volcanic rocks (Aitchison et al., 2007b; McDermid et al., 2002), and Paleogene molasse sediments (Davis et al., 2002).

The Tethys Himalaya can be split into southern and northern units based on the presence of major intervening structures and differences in lithology across the Lhagoi Kangri Anticline (Burg et al., 1987). The southern unit is composed mainly of Proterozoic to Eocene carbonate and clastic sedimentary rocks (Wang et al., 2002; Willems et al., 1996; Zhu et al., 2005a). The deformation and metamorphism of these strata are usually weak. The northern unit consists of Proterozoic to Eocene sandstone, shale, chert and limestone that underwent major shortening and low grade metamorphism (Burg et al., 1985; Chen et al., 2011; Ding et al., 2005; Li et al., 2005a, 2005b Liu and Einsele, 1994, 1996, Wan et al., 2005). A belt of gneiss domes lies along the axis of the Lhagoi Kangri Anticline in the middle part of the Tethys Himalaya and consists of medium- to high-grade metamorphic rocks and Cambrian–Ordovician granites(Leeetal.,2000)and30–10 Maleucogranites(Zhangetal.,2004). 3. Stratigraphy

The upper Cretaceous strata deposited on the Indian passive continental margin in the Gyangze area of south–central Tibet (Fig. 2) are divided from older to younger into the Jiabula Formation, Chuangde Formation and Zongzhuo Formation (Fig. 3).

The Jiabula Formation is 150–1000 m thick and consists of mainly black shale, chert, and minor sandstone (Liu and Einsele, 1994). Belemnite and radiolaria indicate an age of Cenomanian to Coniacian for this formation (Li et al., 2005a, 2005b; Wang et al., 2005).

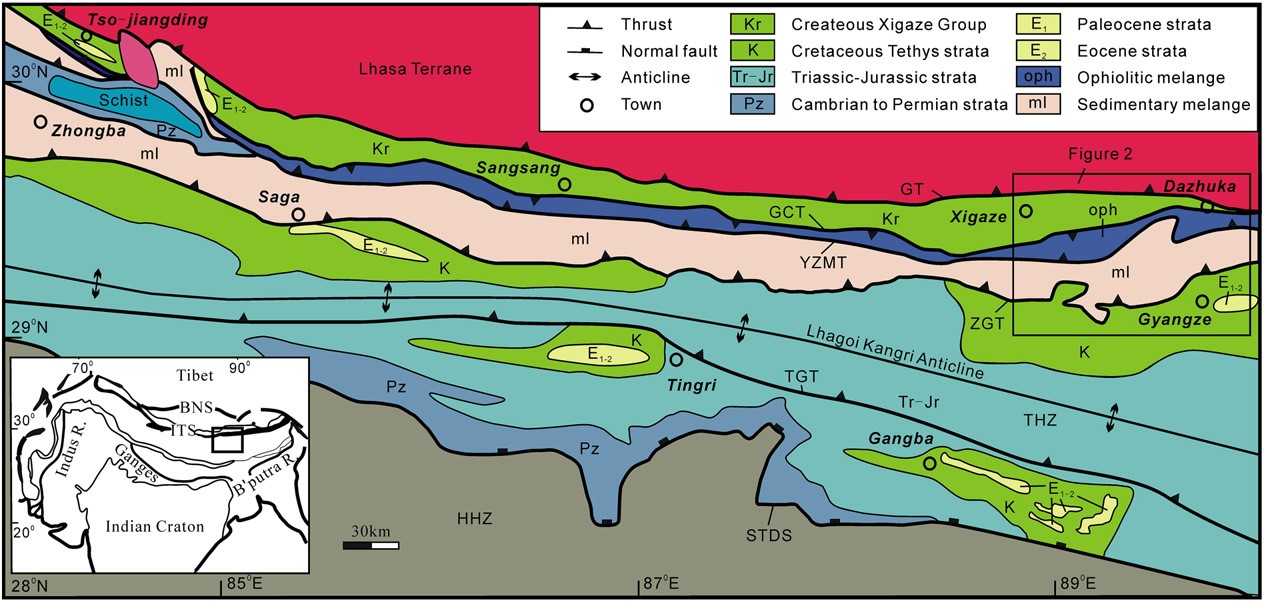


Fig. 1. Simplified geological map of south–central Tibet. GCT = Great counter thrust, YZMT = Yarlung Zangbo mantle thrust, ZGT = Zhongba–Gyangze thrust, STDS = South Tibetan detachment system, THS = Tethys Himalaya sequence, GHS = Great Himalaya sequence. After Ding et al., 2005.

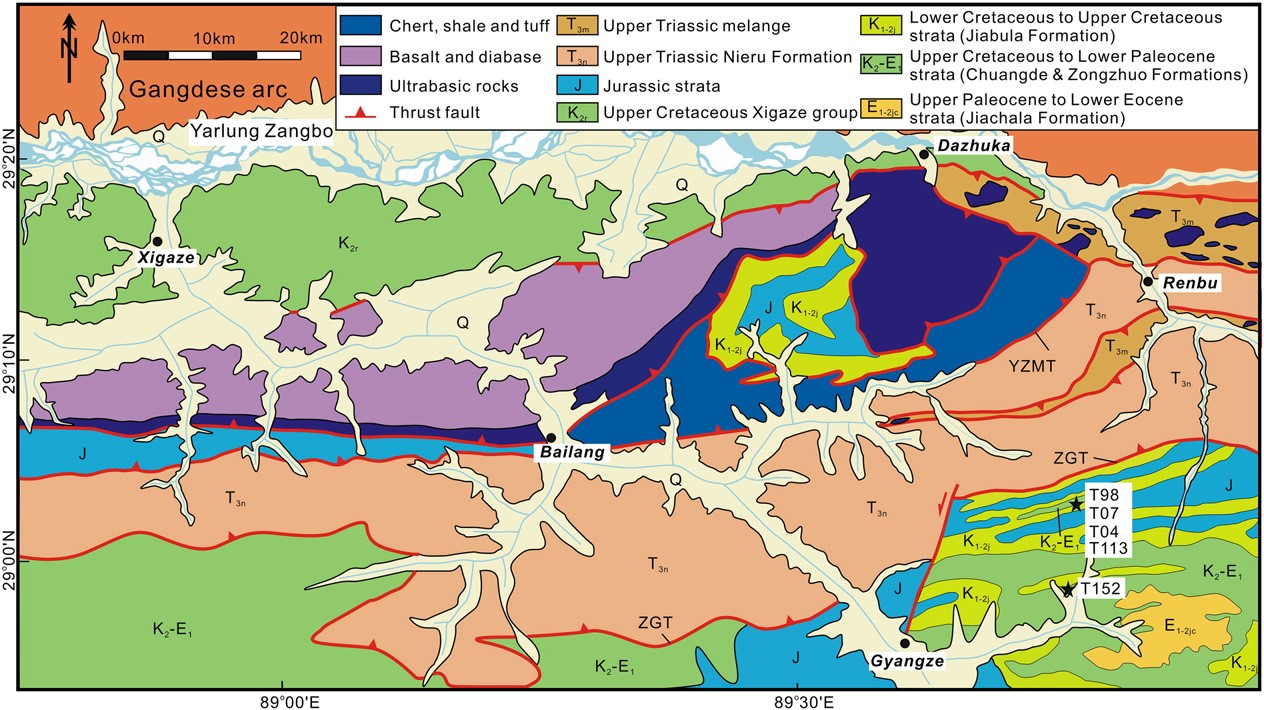


Fig. 2. Simplified geologic map of south–central Tibet in the Xigaze area, modified after a 1:200,000 Gyangze geological map (Wan and Liu, 2005) and 1:200,000 Xigaze geological map (Hu, 2003 YZMT = Yarlung Zangbo mantle thrust, ZGT = Zhongba–Gyangze thrust. Star means sample position, and T152 means sample number.

The Chuangde Formation was deposited conformably on the Jiabula Formation and consists of 20–30 m of violet-red marine shale, thin-bedded pelagic marl, gravity transported limestone and radio-

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| Fig. 3. Measured stratigraphic column for upper Cretaceous sequences in the Gyangze area. The age peaks number in bold is the maximal deposition age of the sample. The age statistics are conducted by Age Pick Program of the University of Arizona (<http://www.geo.arizona.edu/alc/Analysis%20Tools.htm>.). Age sources are as follows: the Jiabula Formation (Li et al., 2005a, 2005b; Wang et al., 2005), the Chuangde Formation (Li et al., 2011; Wan et al., 2005; Wang et al., 2005), and the Zongzhuo Formation (Liu and Aitchison, 2002; Wang et al., 2005). |

larian chert (Chen et al., 2011). Planktonic foraminifera and radiolaria indicate a Santonian to Masstrichtian age for the formation (Li et al., 2011; Wan et al., 2005; Wang et al., 2005).

The Zongzhuo Formation sits conformably on the Chuangde Formation and is predominantly composed of 200–500 m of black shale and thin-bedded yellow-green sandstone enclosing various olistoliths of sandstone, limestone and chert (Li et al., 2005a, 2005b; Wang et al., 2005). The age is Maastrichtian to late Paleocene (Liu and

Aitchison, 2002; Wang et al., 2005). Detailed studies of the Zongzhuo Formation show that the sedimentary environment shifted from continental margin slope to a narrowing remnant and trench basin from south to north (Liu and Einsele, 1996). We documented a succession of conglomerate that is best exposed in a hundred-meterlong belt of outcrops along the south side of Zhongba–Gyangze thrust belt (Fig. 2) and northeast of Rilang village in the form of a big lens (here referred to as the Rilang conglomerate). The Rilang conglomerate is 250 m thick and consists of an upward-thinning and fining succession of matrix-supported cobble-boulder volcaniclastic conglomerate, medium to coarse sandstone, and black mudstone. The conglomerates are dominated compositionally by clasts of volcanic rocks (59%), limestone (19%), sandstone (9%), chert (9%) and diabase (4%). Sedimentary structures in the strata are characteristic of Bouma sequences with A–B–E divisions. The assemblage of lithofacies in this unit is interpreted to indicate the depositional environment of submarine fan (Walker, 1978). The upper fan can be further divided into main culverts with coarse deposits and overflow between main culverts with fine sediments and mud. The middle and lower fans were missing. Measured paleocurrents from long-axis-transverse imbrications of pebbles show a southwest paleoflow direction.

# 4. Methods

## 4.1. U–Pb detrital zircon geochronology

U–Pb detrital zircon geochronology was conducted by laser-ablationmulticollector inductively coupled-plasma-mass spectrometry at the Northwest University in Xi'an, China (for samples T98 and T152) and Institute of Tibetan Plateau Research, Chinese Academy of Sciences (for samples T113, T04, and T07). More detailed analytical procedures and configuration of the LA-ICP-MS have been described in Wu et al. (2007).

70–80 individual zircon grainswere randomly selected and analyzed from each sample. The ages reported in the text are 206Pb/238U ages for grains less than ~1000 Ma and 207Pb/206Pb ages for grains with ages N1000 Ma. Those ages with N10% uncertainly (206Pb/238U) or more than 20% discordance or 5% reverse discordance were discarded from interpretation. Concordia diagrams and age-probability plots are displayed using the programs of Ludwig (2003). All U–Pb–Hf data obtained in this study are listed in Table B in auxiliary material.

## 4.2. Detrital zircon Hf isotope analysis

Zircon Hf isotopic measurements were obtained using a Neptune MC-LA-ICP-MS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. This machine is a double focusing multicollector inductively coupled-plasma-mass spectrometry and has the capability of high mass resolution measurements in multiple collector modes. Zircon standard 91500 was used for external correction. More detailed analytical procedures and configuration of the MC-LA-ICP-MS have been described in Wu et al. (2007).

## 4.3. Whole rock Nd isotope analyses

Rb–Sr andSm–Nd isotopic analyses wereconducted onaVG354 mass spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Whole-rock powders were dissolved in a Teflon beaker after being spiked with 84Sr, 87Rb, 150Nd and 147Sm tracers prior to HF+HNO3 (with a ratio of 2:1) dissolution. Rb, Sr, Sm and Nd were separated by AG50WX8 (H+) exchangeable ion poles. Procedural blanks were b100 pg for Sm and Nd and b500 pg for Rb and Sr. Isotope fractionation was corrected by normalization to 146Nd/144Nd=0.7219, and 87Sr/86Sr ratios normalized to 86Sr/88Sr=0.1194. Typical within-run precision (2 σ) for Sr and Nd was estimated to be ±0.00002 and ± 0.000015, respectively. Analytical details are described by Ding et al. (2003). Sr and Nd isotopic analyses are presented in Table C in the auxiliary material.

## 4.4. Electronic microprobe analyses

Compositions of spinels were determined using a CAMECA SX51 electron microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The accelerating voltage was 21 kV, the sample current was 10 nA, and the beam diameter was 1 μm. Spinels were separated from sandstones of the Zongzhuo Formation and the Rilang conglomerate.

# 5. Results

## 5.1. Sandstone petrology

The sandstone petrographic analyses are displayed as ternary plots in Fig. 4 and presented in Table A in the auxiliary material. For consistency and accuracy, 300 points were counted for each sample using the Gazzi–Dickinson method (Dickinson and Suczek, 1979; Ingersoll et al., 1984; Zuffa, 1980).

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| Fig. 4. Petrography of the Jiabula Formation, the Zongzhuo Formation and the Rilang conglomerate plotted on standard QpLvLs, QtFL, and QmFLt diagrams (Dickinson, 1985). F = feldspar, L = lithic, Lt = total lithics, Ls = sedimentary lithics, Lv = volcanic lithics, Qm = monocrystalline quartz, Qp = polycrystalline quartz, Qt = total quartz. |

In sandstones of the Jiabula Formation, well-sorted, subrounded to subangular quartz (83%) dominates over lithic fragments (6%) and feldspar (11%). Quartz grains are mostly monocrystalline and do not show considerable undulosity. Sedimentary lithic fragments (4%) include sandstone and shale. Volcanic lithic fragments (2%) are negligible in this formation. No metamorphic detritus was observed. Accessory minerals includezircon,pyrite,ilmeniteandrutile.NoCr–spinelwasfound.InFig.4, the quartz-rich, lithic-poor Jiabula sandstones plot at the boundary of the continental block and recycled orogen provinces on the QtFL diagram and in the continental block province on the QmFLt diagram.

Sandstones in the Zongzhuo Formation are dominated by quartz grains (monocrystalline and polycrystalline) and lithic fragments, often poorly sorted with angular to subangular shapes. Quartz is mainly monocrystalline (50%) and shows undulose extinction. Polycrystalline quartz is all chert (6%). Feldspar (9%) is a minor phase and shows twinning. Lithic fragments are abundant and constitute approximately 35% of total framework grains which are mainly volcanic fragments (28% of total grains). Textures indicate that volcanic fragments are commonly intermediate in composition and consist of plagioclase phenocrysts in a fine-grained or aphanitic groundmass. Sedimentary lithics (3%) consist of sandstone and shale. Metamorphic lithics (4%) are schists. Accessory minerals include limonite, zircon, tourmaline, rutile and Cr–spinel. The relatively quartz-poor and lithic-rich Zongzhuo sandstones plot in the recycled orogenic provenance field (Fig. 4).

Sandstones in the Riling conglomerate are dominated by feldspar (41%) and lithic fragments (35%), often poorly sorted with angular to subangular shapes. Quartz mainly occurs as polycrystalline chert (6– 21%). Monocrystalline quartz is minor, and shows uniform extinction, suggestive of a volcanic origin. Volcanic lithic fragments are abundant and consist of mainly intermediate volcanic rock fragments similar to those in the Zongzhuo Formation. Accessory minerals include epidote, limonite, zircon, and Cr–spinel. The relatively quartz-poor, lithic-rich and feldspar-rich Rilang sandstones plot in the magmatic arc provenance filed (Fig. 4).

## 5.2. U–Pb–Hf detrital zircon results

Samples T113 and T04 were collected from the upper part of the Jiabula Formation (Fig. 3). Zircon crystals are mainly rounded to subrounded and yielded Th/U ratios of 0.11–2.6. 140 analyses yield 132 usable ages (Fig. 5). The age spectra of these two samples show a major peak at 500 Ma, a small population at 1000 Ma, and some ages scattered between 3257 Ma and 1290 Ma (Figs. 5 and 6).

Sample 152 was collected from the lower part of the Zongzhuo Formation which is just 10 m above the red limestone of the Chuangde Formation (Fig. 3). Zircon crystals are euhedral and yielded Th/U ratios of 0.18–1.88. 80 and analyses yield 76 usable ages (Fig. 5). The minimum zircon age is 90 Ma. The largest detrital zircon age population lies within the 169–73 Ma range. There are smaller populations in the ranges of 796– 517 Ma, 1288–911 Ma, and 1836–1412 Ma, and some scattered ages between 2753 and 2537 Ma (Fig. 6). 28 detrital zircons from this sample were also analyzed for Hf isotopic compositions (Fig. 7). Most of the Mesozoic zircons display high 176Hf/177Hf isotopic ratios of 0.282826– 0.283072 that yield positive εHf(t) values of +5.0–+13.0 and two-stage Hf model ages of 695–437 Ma. Most pre-Mesozoic zircons have low 176Hf/ 177Hf isotopic ratios of 0.281101–0.282364 that yield εHf(t) values of −11.7~+8.4 and two-stage Hf model age of 3671–1671 Ma. Sample T07 was collected from the upper part of Zongzhuo Formation, just 5 m below the Rilang conglomerate (Fig. 3). Zircon crystals are euhedral and yielded Th/U ratios of 0.28–2.35. 70 and analyses yield 64 usable ages (Fig. 5). The minimum zircon age is ~93 Ma. The largest detrital zircon age population is at 100 Ma, there are some scattered ages at 1060 Ma, 1090 Ma, and 3044 Ma (Fig. 6).

Sample 98 was collected from the lower part of Rilang conglomerate (Fig. 3). Zircon crystals are euhedral and yielded Th/U ratios of 0.15–1.49. 80 and analyses yield 62 usable ages (Fig. 5). The youngest zircon age cluster is at 90 Ma. The largest detrital zircon age population is within the range of 146–90 Ma. There are also some scattered ages at 172 Ma, 178 Ma and 1087 Ma (Fig. 6). 17 detrital zircons from this sample were also analyzed for Hf isotopic compositions (Fig. 7). All Mesozoic zircons display high 176Hf/177Hf isotopic ratios of 0.282929–0.283159 that yield positive εHf(t) values of +9.7–+16.7 and two-stage Hf model ages of 756–116 Ma.

## 5.3. Sm–Nd bulk rock data

Sr and Nd isotopic ratios were not age-corrected. Sandstone of the ZongzhuoFormationyield87Sr/86Sr=0.715098,143Nd/144Nd=0.512111, εNd(0)=−10.27, and TDM=1.59 Ga. Sandstone of the Rilang conglomerate has 87Sr/86Sr=0.706065, 143Nd/144Nd=0.512736, εNd(0)=1.92, and TDM=0.79 Ga. The isotopic character of Rilang conglomerate is more isotopically juvenile than that of the Zongzhuo Formation.

## 5.4. Chromium–spinel compositions

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| Fig. 5. U–Pb concordia diagrams of zircon grains. Samples were collected from late Cretaceous strata of the Tethys Himalaya, in the Gyangze area. |

Cr–spinel data were present in Cai et al. 2008. We cited and made further discussion in this text. Chromium–spinel compositions of the Zongzhuo Formation are characterized by low TiO2 (generally b0.1%) and a Cr number mainly between 70 and 80. Detrital chromium–spinels from sample T98 of the Rilang conglomerate have high TiO2 (generally N0.2%) and a Cr number mainly between 70 and 85; other spinels in the Rilang conglomerate sandstones are characterized by low TiO2 (generally b0.2%) and a Cr number mainly between 60 and 90 which are similar with those of the Zongzhuo Formation.

# 6. Discussion

## 6.1. Zircon provenance

### 6.1.1. Review of geochronological data from different terranes

In order to discriminate provenances of the upper Cretaceous strata of the northern Tethys Himalaya in Gyangze, southern Tibet, we review the published U–Pb geochronologic zircon data from the Indian craton, the Lesser Himalaya, the Higher Himalaya, the Tethys Himalaya, the Yarlung Zangbo suture zone and the Lhasa terrane (Fig. 6).

Indian craton detrital zircons are characteristic of ages between Archean and Proterozoic (DeCelles et al., 2004 and references therein). The Lesser Himalayan detrital zircons have age population peaks at 1850 Ma and 2500 Ma (Richards et al., 2005). The Higher Himalayan detrital zircon ages are broadly clustered about 1100 Ma, with lesser peaks at 500 Ma, 1700–1500 Ma, and 2500 Ma (DeCelles et al., 2000; Gehrels et al., 2003, 2006; Martin et al., 2005; Parrish and Hodges, 1996; Richards et al., 2005).

The Tethys Himalaya has age patterns similar to those of the Higher Himalayan detrital zircons (Fig. 6). However the younger population of ~500 Ma is much more prominent than other peaks in the Tethys Himalaya (Amos et al., 2008; DeCelles et al., 2000; Myrow et al., 2003). There are also small populations ranging from 140 to 110 Ma in Nepal, which were interpreted to have been derived from Indian volcanic rocks (DeCelles et al., 2004). The Triassic strata near Zedong and Renbu in southern Tibet show age peaks between 400 Ma and 200 Ma (Amos et al., 2008; Li et al., 2010). Volcanic rocks of the Sangxiu volcanic rocks yield U–Pb age of 133 Ma (Zhu et al., 2007). Lower Cretaceous Wolong volcaniclastics yield U–Pb age from 140 Ma to 119 Ma, and εHf(t) values from −1.5 to −7.2 (Hu et al., 2010).

The Yarlung Zangbo suture zone shows relatively simple age patterns. Suture-zone gabbros yield U–Pb zircon ages of 162 Ma and 126 Ma (Malpas et al., 2003; Zhong et al., 2006).The Zedong island arc volcanic rocks within the suture zone yield U–Pb ages of 161–152 Ma (McDermid et al., 2002).

The Lhasa terrane includes the Gangdese arc rocks in the south as well as plutons and volcanogenic strata in the north. Zircon U–Pb dating indicates that plutonic rocks within the Gangdese arc have ages ranging from 140 Ma to 8 MawithpositiveεHf(t) (Chuetal., 2006;Jietal., 2009; Wu et al., 2007; Zhu et al., 2008, 2009). The Linzizong volcanic rocks erupted during the 69–43 Ma time interval (He et al., 2007). The Gangdese arc also includes older granites and volcanic rocks with crystallization ages in the 237–163 Ma range and highly variable εHf(t) from −13.7 to +17.7 (Chu et al., 2006; He et al., 2006; Li et al., 2003; Liu et al., 2006; Zhang et al., 2007; Zhu et al., 2008). By contrast, the ages of volcanic rocks in northern Lhasa terrane range from 139 to 102 Ma with negative εHf(t) (Zhu et al., 2009). Zircons from the sedimentary strata of the Lhasa terrane have age population peaks at 200–100 Ma, 500 Ma, and 1000 Ma (DeCelles et al., 2007; Leier et al., 2007a, 2007b).

### 6.1.2. Interpretations of detrital zircons

Detrital zircons from the Jiabula Formation have age population peaks at 500 Ma and 1000 Ma, which is similar to those of Cambrian and younger strata within the Tethys Himalaya and Lhasa terrane(Fig. 6). However, the Lhasa terrane source was impossible, because the old grains are not accompanied by abundant Cretaceous zircon grains. Scarcely Cretaceous zircon grains were consistent with those found in Nepal which were derived from volcanic provinces in India (DeCelles et al., 2004). Thus the source is most likely to be Indian plate.

Detrital zircons from the Zongzhuo Formation show a peak in the range of 169–73 Ma which indicates that they were derived from Jurassic to Cretaceous rocks. Zircon Hf compositions show that the source rocks are juvenile (Fig. 7). A likely source for the Mesozoic zircons is the Gangdese arc. The whole pattern of detrital zircons from this formation is also similar with that of Xigaze forearc basin strata which were derived from Gangdese arc and northern Lhasa terrane (Wu et al., 2010).

Most of zircons analyzed from the Rilang conglomerate show Mesozoic ages. As shown in Fig. 7, the majority of these Mesozoic zircons reveal positive εHf(t) values similar to those from the Zongzhuo Formation. The zircon data lead us to concur with the conclusion that the Gangdese arc may be the main source of detritus within the Rilang conglomerate.

## 6.2. Cr–spinel provenance

Lenaz et al. (2000) set a compositional boundary between peridotitic and volcanic spinels at TiO2=0.2 wt.%. Spinels from the Zongzhuo Formation and upper part of the Rilang conglomerate usually have TiO2 content b0.2%, and are therefore most likely derived from peridotites. However, most of spinels in sample T98 from the lower part of the Rilang conglomerate have TiO2 content N0.2%, and are thus interpreted to be volcanic spinels.

In the plot of TiO2 vs. Al2O3 (Fig. 8a), spinels from sample T98 of the Rilang conglomerate fall in alkaline island arc area, whereas all the other spinels fall in suprasubduction zone area (SSZ).

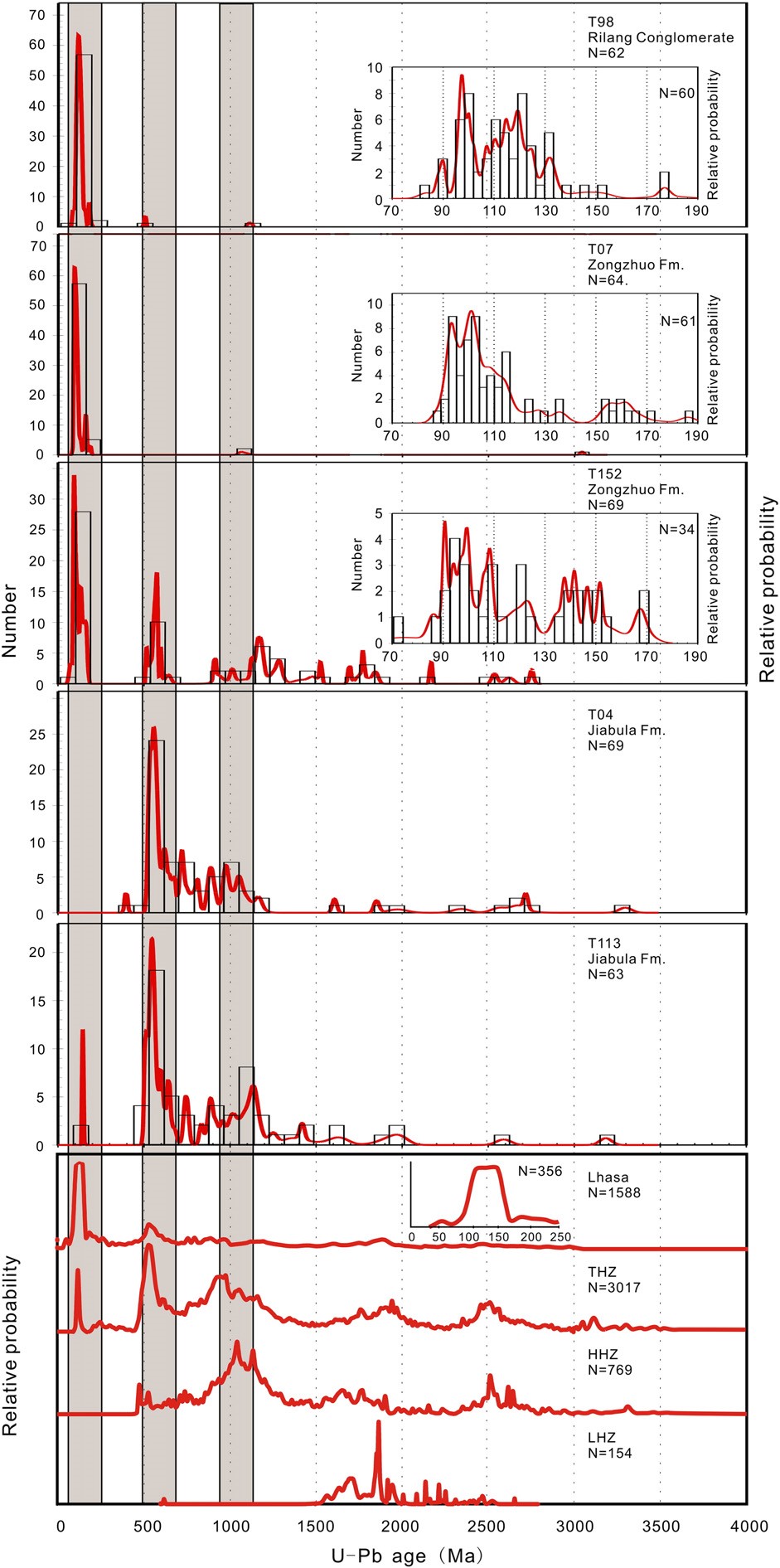
In the plot of Cr# vs. Mg# (Fig. 8b), according to the classifications of Dick and Bullen (1984), spinels from the Zongzhuo Formation and Rilang conglomerate correspond best with spinels in Type III peridotites which are generally associated with arc-related volcanic and intrusive rocks.

Considered together, the plots of TiO2 vs. Al2O3 and Cr# vs. Mg# demonstrate that spinels of the Zongzhuo formation and the Rilang conglomerate are best assigned to bed rocks from suprasubduction zone mantle peridotites and arc volcanic rocks (Kamenetsky et al., 2001). Spinels in this study are different to the compositions of detrital spinels in Xigaze ophiolitic rocks (Fig. 8) and closely match that of spinels from Luobusa ophiolites which formed above an intraoceanic subduction zone (Zhou et al., 1996). Therefore, spinels of the Zongzhuo Formation and Rilang conglomerate were most likely derived from an intra-oceanic subduction system.

## 6.3. Nd-isotopic provenance

Whole rocks from the Indian craton have very low εNd(0) values, usually more negative than −30 (Saha et al., 2004). Whole rocks from the Lesser Himalaya have εNd(0) values between −25 and −20 (Ahmad et al., 2000; Martin et al., 2005; Parrish and Hodges, 1996; Robinson et al., 2001). Whole rocks from the Higher Himalaya have εNd(0) between −18 and −13 (Ahmad et al., 2000; Martin et al., 2005; Parrish and Hodges, 1996; Richards et al., 2005; Robinson et al., 2001; Takeshi and Kazunori, 2008). Whole rocks from the southern Tethys Himalayan have εNd(0) between −19 and −11(Ahmad et al., 2000; Dai et al., 2008; Richards et al., 2005; Robinson et al., 2001). In contrast to published data, the

Fig. 6. Relative age probability curves of detrital zircons from upper Cretaceous strata of the Tethys Himalaya, in the Gyangze area. Gray rectangles highlight age peaks in the range of 200–70 Ma, 700–500 Ma and 1200–1000 Ma. Data sources are as follows: the Lesser Himalaya (Richards et al., 2005); the Higher Himalaya (DeCelles et al., 2000; Gehrels et al., 2003, 2006; Martin et al., 2005; Parrish and Hodges, 1996; Richards et al., 2005); the Tethys Himalaya (Myrow et al., 2003; DeCelles et al., 2000, 2004; Amos et al., 2008;Li et al., 2010); and Lhasa terrane (Li et al., 2003; Kapp et al., 2005; Chu et al., 2006; Liu et al., 2006; He et al., 2006; DeCelles et al., 2007; He et al., 2007; Leier et al., 2007a, 2007b; Wu et al., 2007 and references therein; Zhang et al., 2007; Zhu et al., 2008, 2009; Ji et al., 2009; Wu et al., 2010).



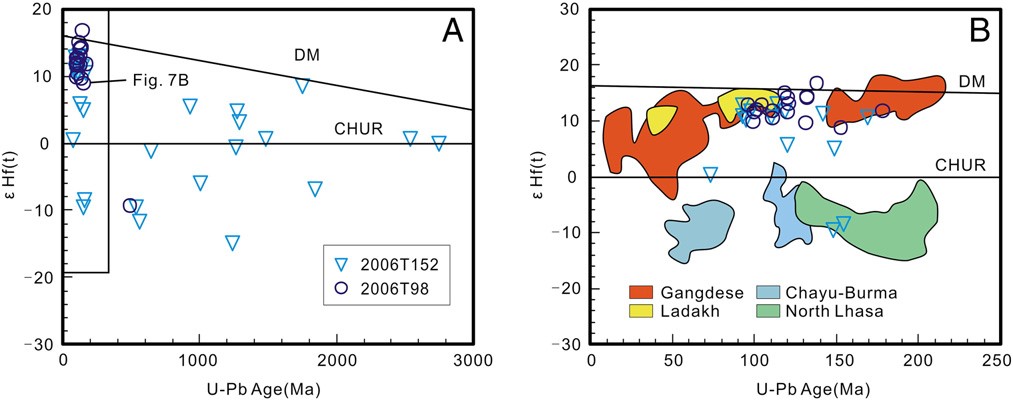


Fig. 7. Hf isotopic features of detrital zircons from the upper Cretaceous strata of the Tethys Himalaya in the Gyangze area. The compositional areas shown in (B) are from Liang et al.,

2008. Depleted Mantle (DM), Chondritic Uniform Reservoir (CHUR).

sample from the Zongzhuo Formation has εNd(0)=−10.27 which is higher than that of the Tethys Himalaya rocks and indicates input of juvenile detritus. The sample from the Rilang conglomerate has positive εNd(0)=1.92 and low Sr and therefore was derived mainly from a juvenile source. The Nd isotopic data indicate that both samples in this study aremore isotopicallyjuvenilethantheTethys Himalaya,theHigher Himalaya, and the Lesser Himalaya. Input of arc material as shown by εNd(0) is consistent with the results of petrology, the presence of arcrelated spinel, and the detrital zircon U–Pb–Hf data.

## 6.4. Cretaceous strata provenances

Combining field observations, together with petrologic, detrital zircon U–Pb–Hf, Cr–spinel composition and bulk rock Nd-isotopic data, the simplest explanation of provenances of the late Cretaceous strata is as follows:

Samples from the Jiabula Formation are quartz-rich and lithicpoor, showing signatures of a continental block provenance. Detrital zircons show an Indian provenance and are consistent with conclusions from petrology and Cr–spinels geochemistry of the Tianba flysh which also indicated an Indian continent provenance (Zhu et al., 2005b). The fact that no Cr-spinels from the Yarlung Zangbo suture zone and Cretaceous zircons from the Gangdese arc are present in this formation indicates that the Gangdese arc-trench system did not supply sediments to the Jiabula Formation.

Samples from the Zongzhuo Formation are lithic-rich and relatively quartz-poor and show signatures of a recycled orogenic provenance. Besides the N500 Ma zircons derived from the Tethys Himalaya or Lhasa terrane, a sudden influx of Cretaceous-age zircons with positive εHf(t) and intermediate volcanic fragments indicates a source of sediment from a juvenile arc. The Nd isotopic data support the above zircon data and indicated that the Zongzhuo Formation is more isotopically juvenile than that of the Tethys Himalaya. The presence of Cr–spinels with SSZ affinity indicates that Neo-Tethys oceanic crust was also a source area. Therefore, the Zongzhuo Formation is interpreted to have mainly been shed from northern suture zone and Gangdese arc. While the provenance of old detrital zircons (N500 Ma) is not clear.

The Rilang conglomerate is characteristic of gravity flows. Samples are feldspar- and lithic-rich and monocrystalline quartz-poor, showing signatures of arc provenance and trench facies. Detrital zircons are almost all Mesozoic in age and show positive εHf(t) values. Combined with positive εNd(0) and Cr–spinels with arc affinity, detritus of the Rilang conglomerate were mainly derived from a juvenile arc and suture zone. Paleocurrent data indicate that the source was located to the north of the location where the conglomerate was deposited. The values of εNd(0) shifted from negative for the Zongzhuo Formation to positive for the Rilang conglomerate and the decrease of number of old zircon (N500 Ma) grains indicates increasing contributions from the arc and suture zone. Therefore, Rilang conglomerate is interpreted to have totally been shed from northern suture zone and Gangdese arc.

## 6.5. Tectonic evolution

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| Fig. 8. (A) TiO2 vs. Al2O3 and (B) Cr# [Cr/(Cr+Mg)] vs. Mg# [Mg/(Mg+Fe2+)] diagrams for detrital chromium–spinels from the Zongzhuo Formation and the Rilang conglomerate. Fields in Fig. 8 (A) are based on the study of Kamenetsky et al. (2001). Fields in Fig. 8 (B) are based on the study of Dick and Bullen (1984)). The Xigaze ophiolite field is based on the analysis of Wang et al. (1999). The Luobusa ophiolite field is based on the analysis of Zhou et al. (1996). Continental Flood Basalts (CFB), Ocean Island Basalts (OIB), Mid-Ocean Ridge Basalts (MORB), Supra-subduction zone (SSZ). |

We present two contrasting models for the evolution history of the Neo-Tethys Ocean in south–central Tibet which both can explain the transition from southern Indian provenance of the Jiabula Formation to a northern arc and suture zone provenance of the Zongzhuo Formation and the Rilang conglomerate (Fig. 9).

Model 1: Juvenile arc material represents Gangdese arc.

The Gangdese arc consists of Mesozoic and Cenozoic magmatic rocks derived from a juvenile mantle source (Chu et al., 2006; Ji et al., 2009; Mo et al., 2007; Wen et al., 2008; Zhu et al., 2008;), which could have supplied detrital materials for the Zongzhuo Formation and the Rilang conglomerate (Fig. 9A).

During the latest Cretaceous, it has been proposed that the Gangdese arc had already been uplifted to significant elevation and could have shed sediments to basins to both the north and south (DeCelles et al., 2007; Ding and Lai, 2003; Kapp et al., 2005; Kapp et al., 2007; Leier et al., 2007b; Murphy et al., 1997; Wu et al., 2010). Although the fore-arc basin includes Paleocene–Eocene marine strata in the Tso-jiangding area to the west of our study area (Ding et al., 2005), it could have been overfilled in the Xigaze area (Dürr, 1996; Einsele et al., 1994) with sediments shed from the Gangdese arc (Dürr, 1996; Wu et al., 2010), and became a shallow platform setting marking the end of the forearc basin (Wan et al., 1997). Therefore, detrital sediments could deposit further south to the Indian passive margin across the Xigaze forearc basin which is confirmed by the similarity of detrital zircon patterns between the Zongzhuo Formation and the strata of Xigaze forearc basin (Wu et al., 2010). Meanwhile, the Zongzhuo Formation and the Rilang conglomerate included detrital sediments from the accretionary prism (Liu and Einsele, 1996) and the Gangdese arc, which indicates initial contact between the Indian plate and Lhasa terrane at that time.

Provenance of the upper Cretaceous strata changed during the deposition of Chuangde Formation in Gyangze area. This similar change is also observed in Saga area (Ding, 2011, unpublished data). Therefore, the transition from the southern Indian provenance of the Jiabula Formation to the northern Gangdese arc source of the Zongzhuo Formation and Rilang conglomerate indicates that the initial collision between the India and Asia plates occurred during Maastrichtian (~70–65 Ma).The initial collision caused flexure of the downgoing Indian plate, and may be responsible for the drastic sedimentary pattern changes from continental shelf to slope (Willems et al., 1996) and the sharp increase in the rate of tectonic subsidence curve (Rowley, 1998), which were observed near Tingri at about 68 Ma in the southern Tethys Himalaya. The initial collision also caused the deformation of the overriding Lhasa terrane, as recorded by major shortening of the late Cretaceous Takena Formation prior to early Tertiary Linzizong Group volcanism.

Paleomagnetism is an effective approach for quantifying paleogeography and constraining plate paleopositions. Paleomagnetic studies show that the southern margin of Lhasa terrane was located at 11.5°N±6.2° during the deposition of the late Cretaceous Takena Formation (Achache et al., 1984). In contrast, the northern margin of the Indian continent was located at ~5°S±5° during 71–65 Ma (Chen et al., 2010; Dupont-Nivet et al., 2010; Patzelt et al., 1996). Though detailed problems such as the shape and extent of greater India (Ali and Aitchison, 2005), secondary remagnetization (Patzelt et al., 1996), and inclination shallowing (Tan et al., 2010) are still debated, there is an agreement that there was still a huge gap between the Greater Indian continental margin and the Lhasa terraneduringthelatestCretaceous(Chenetal.,2010;Dupont-Nivetetal., 2010; Liebke et al., 2010). Therefore, detrital sediments from the Lhasa terrane were impossible to deposit onto the Indian passive continental margin during late Cretaceous. This makes the early collision unreasonable. However, large uncertainties and low quality remain in existing paleomagnetic data, and paleomagnetic studies just provide a minimum age of initiation of India–Asia collision. Future study will help estimate the paleolatitude of the southern margin of Asia and northern margin of Tethys Himalaya and thus constrain the precise paleo-position.

Initial collision between the India plate and Lhasa terrane during Maastrichtian (~70–65 Ma) is challenged by the enormous amount of subsequent intracontinental shortening required. Early India–Asia collision predicts at least 2000 km of intercontinental shortening between 70 Ma and 55 Ma based on the relative convergence rate between India and Asia (Copley et al., 2010). No Paleocene shortening in the Tethys Himalaya and minimal Paleocene shortening in southern Lhasa terrane make this impossible (Ding et al., 2005). However this record could have been totally subducted beneath the Lhasa block along the YZSZ or occurred further to the north within the entire Tibetan plateau (Yin and Harrison, 2000). Alternatively, the convergence rate is based on the hypothesis that the motion of Indian is relative to the stable Eurasia (Patriat and Achache, 1984). Considering the Eurasia was unstable and moving toward north, the real intracontinental shortening would be smaller than 2000 km.

Model 2: Juvenile arc material represents a disappeared intra-oceanic arc.

An intra-oceanic oceanic arc could be active during 140–80 Ma within the Tethys Ocean based on our detrital zircon data from the Zongzhuo Formation and the Rilang conglomerate. Therefore, the first appearance of Cretaceous zircons with positive εHf(t) and intraoceanic arc-related spinels record the obduction of an intra-oceanic subduction system onto the Indian passive continental margin during Maastrichtian (~70–65 Ma) (Fig. 9C).

The continental Gangdese arc may have transitioned northwestward into the intra-oceanic Kohistan arc in northern Pakistan and northwestern India which was active during Aptian–Cenomanian (Rolland et al., 2002), and collided with the Karakorum block at 85– 80 Ma (Searle et al., 1999). In Zedong to the east of our study area, geochemical studies indentify a suite of intra-oceanic arc volcanic rocks (Aitchison et al., 2007b). These findings confirm that the interior framework of the Neo-Tethys Ocean was complex and contained one or more intro-oceanic subduction systems. The intro-oceanic arc in south–central Tibet first collided with the Indian passive continent margin (Fig. 9B), that is different to the Kohistan arc. The relationship between the intra-oceanic arc in this study and the Kohistan arc in north Pakistan is not clear.

The intra-oceanic subduction system in south–central Tethys ocean generated ophiolites showing intra-oceanic arc and back-arc basin signatures (Bedard et al., 2009; Dubois-Côté et al., 2005) and Beimarang mélange which was interpreted as an obduction mélange formed near a spreading ridge (Huot et al., 2002). The remnants of subducted slab along the intra-oceanic subduction zone were preserved in mantle which should be responsible for the deeper-mantle anomaly zone (Van der Voo et al., 1999). The obduction of oceanic crust along an intra-oceanic subduction zone can also explain the drastic sedimentary pattern changes from continentalshelf toslope(Willems et al., 1996), thesharp increase in the rate of tectonic subsidence near Tingri (Rowley, 1998), and the influx of accretionary prism materials (Liu and Einsele, 1996).

The scarcity of Cretaceous arc fragments in southern Tibet may be explained by complete northward underthrusting beneath the southern Asian margin (Makovsky et al., 1999).

However, considering no accepted intro-oceanic arc was found and the possibility that the very southern edge of the Gangdese arc was built on oceanic crust and thus it also exhibits characteristics of an oceanic arc, we tentatively prefer option (1). Future studies of precise chronostratigraphy of the late Cretaceous strata in northern Tethys Himalaya and post-collision shortening through the Tibetan plateau and high quality Paleomagnetic data have potential to reveal the initial process of the India–Asia collision.

# 7. Conclusions

In-situ U–Pb–Hf isotopic from detrital zircons, bulk rock Nd isotopic and Cr–spinel analysis and petrographic data from the upper Cretaceous clastic sedimentary rocks of the northern Tethys Himalaya near Gyangze, southern Tibet have lead to the following major conclusions:

1. The Jiabula Formation was derived from the Indian continent.
2. The Zongzhuo Formation and Rilang conglomerate contain abundantCretaceous zircon grains with positive εHf(t) and arc-related Cr–spinels

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| Fig. 9. (A) The juvenile arc source of sediment to the upper Cretaceous Zongzhuo Formation and Rilang conglomerate represents the Gangdese arc. In this scenario, initial collision between India and Asia occurred during Maastrichtian (~70–65 Ma). (B) An alternative model in map view of the double subduction systems, in which the northern subduction system is responsible for the formation of Gangdese arc and Kohistan–Ldakh arc, whereas the southern subduction system is responsible for the formation of an intra-oceanic island arc. (C) The alternative model in cross-section view showing the juvenile arc to represent a disappeared intra-oceanic arc. The appearance of Cretaceous zircons with positive εHf(t) and arc-related spinels indicate the obduction of an intra-oceanic subduction system onto the Indian passive continental margin during Maastrichtian (~70–65 Ma). |

indicating a juvenile arc source. The maximal deposition age provided by detrital zircon ages is 90 Ma. U–Pb isotopic data indicate that the juvenile arc was active during the 146–80 Ma time interval.

1. The sudden appearanceof Cretaceouszirconswith positiveεHf(t) and arc-related Cr–spinels can be interpreted as initial collision between the Indian and Asian plates during Maastrichtian (70–65 Ma).

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