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India-Asia convergence: Insights from burial and exhumation of the Xigaze forearc basin, south Tibet

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Key Points:

- Northward younging trend in cooling ages of Xigaze forearc basin
- Exhumation history linked to changes in India-Asia convergence rates
- Sedimentation in Xigaze basin probably continued until latest Eocene

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Abstract

[1] The composite forearc/syn-collisional Xigaze basin in south Tibet preserves a key record of India-Asia collision. New apatite fission track and zircon (U-Th)/He data from a N-S transect across the preserved fore-arc basin sequence near Xigaze show a consistent northward Late Cretaceous to Middle Miocene younging trend, while coexisting apatite (U-Th-Sm)/He ages are all Miocene. Corresponding detrital zircon U-Pb data are also reported for constraining the Cretaceous depositional ages of the Xigaze basin sequence in the region. Thermal history modelling indicates that the basin experienced northward propagating episodic exhumation, along with a northward migration of the depocenter and that a pre-existing Cenozoic syn-collisional basin sequence which had been removed. In the southern part, forearc exhumation commenced in the Late Cretaceous ($\sim 89 \pm 2$ Ma). Following transition to a syn-collisional basin in the Paleocene, sedimentation in the central and northern Xigaze basin continued until the latest Eocene ($\sim 34 \pm 4$ Ma). Ongoing folding and thrusting (e.g. Great Counter Thrusts) caused by progressive plate convergence during Late Oligocene-Early Miocene time resulted in regional uplift and considerable basin denudation, which fed two fluvial basins along its northern and southern flanks and exposed the basement ophiolite. Subsequent incision of the Yarlung River resulted in Miocene cooling in the region. Different episodes in the exhumation history of the Xigaze basin caused by thrusting of an accretionary wedge and ophiolitic basement, can be linked to changes in

India-Asia convergence rates and the changing subduction pattern of the Indian and Neo-Tethyan slabs.

1 Introduction

[2] Subduction-related forearc and collision-related syn-collisional basins locate on the continental margin, preserve significant information regarding the erosional and magmatic record of continental margins and the pre/syn/post-collision history between continents, and therefore form important archives of continental dynamics [DeCelles *et al.*, 2011; Noda, 2016]. Along the southern margin of the Asian plate, the Xigaze basin includes a forearc basin that transitioned into a syn-collisional basin following collision [e.g. DeCelles *et al.*, 2014]. While much of the younger syn-collisional basin component was denuded during subsequent regional uplift, the thermal imprint revealed by the thermochronological history of preserved basin sediments potentially provides a unique record of India-Asia convergence.

[3] The Xigaze forearc basin, also known as the Gangdese forearc basin, preserves a >4 km thick sedimentary section and was formed along the Indus-Yarlung Suture Zone in the Himalayan orogenic belt. It extends laterally for ~600 km across southern Tibet, linking up with a coeval fore-arc basin in Ladakh further west [Hu *et al.*, 2016b; Figure 1]. The younger basin sequence is only partly preserved in SW Tibet near Zhongba (Figure 1). Previous work has included studies of paleontology, sedimentology, petrography and provenance analysis and mainly focused on depositional processes [e.g. Einsele *et al.*, 1994; Dürr, 1996; An *et al.*, 2014; Orme *et al.*, 2014]. The post-depositional uplift and exhumation

history of the basin during the course of India-Asia collision, however, has received very little attention. Further, the timing of structural emplacement of the supra-subduction zone (SSZ) Xigaze ophiolite, which is considered as basement to the basin [Wang *et al.*, 2012; Huang *et al.*, 2015; Maffione *et al.*, 2015] is not well constrained.

[4] Low temperature (low-T) thermochronology methods, including zircon/apatite U-Th/He (ZHe and AHe, respectively) and apatite fission track (AFT), and have been widely used to reconstruct burial histories and exhumation processes of sedimentary basins [e.g. Garver *et al.*, 1999; Armstrong, 2005]. Here, we present a suite of low-T thermochronology data for locations covering a N-S sampling transect across the Xigaze forearc basin near Xigaze (Figures 1-2), which is the widest and most continuous exposed record of the well-studied lower basin Cretaceous sequence [e.g. Einsele *et al.*, 1994; Wan *et al.*, 1998; Wang *et al.*, 2012; An *et al.*, 2014], and is likely to provide a more complete thermal history record. These data are used to constrain the burial and exhumation history of the basin from Cretaceous time, particularly following the initial India-Asia collision at about $\sim 59 \pm 1$ Ma [according to studies on the Middle Paleogene Sangdanlin Formation sequence in the Tethyan Himalaya, e.g. DeCelles *et al.*, 2015; Wu *et al.*, 2015; Hu *et al.*, 2015, 2016], and the process of exhumation of the Xigaze ophiolite. Furthermore, corresponding detrital zircon U-Pb data were analysed to determine depositional ages of these Xigaze basin sequences. Together these data shed further light on understanding how continental margins may respond to continental collision through time, in this case relevant to India-Asia collision.

2 Regional geological setting

[5] The main India-Asian collision zone in south Tibet separates the Mesozoic-Early Cenozoic Asian plate (e.g. Lhasa and Qiangtang terranes) to the north from the Indian plate to the south. From north to south, the zone in the south Tibet mainly comprises the Gangdese arc, Xigaze basin, Indus-Yarlung Suture Zone, Tethyan, Greater and Lesser Himalaya; Figure 1). (1) The Gangdese magmatic arc (Trans-Himalaya), extending ~2500 km along the south Asia margin (locally Lhasa terrane), mainly includes plutons and intermediate Upper Triassic to Upper Miocene volcanic rocks (e.g. Sangri Group, Yeba Formation, and Linzizong Group), which was linked to the Neo-Tethyan oceanic northward subduction [e.g. *Schärer et al.*, 1984; *Ji et al.*, 2009; *Zhu et al.*, 2013]. However, the Triassic-Jurassic magmatism has also been considered as a result of southward subduction of the Bangong-Nujiang Ocean during that time [*Zhu et al.*, 2015]. The Latest Oligocene- Early Miocene Great Counter Thrusts (GCT) or Late Oligocene Gangdese Thrust (GC) borders the Gangdese belt to the south [*Yin et al.*, 1999; *Murphy and Yin*, 2003; *Murphy et al.*, 2009]. The north-dipping Gangdese Thrust has been proposed as a continuous structure along the entire Gangdese batholith margin [*Yin et al.*, 1999]. However, *Aitchison et al.* [2003] argued for the existence of this thrust along the entire suture zone. (2) The Xigaze basin, is composed of deep-marine turbidites-dominated Cretaceous forearc Xigaze Group (Chongdui and Ngamring formations) and the shallow marine to nonmarine Paleocene - Lower Eocene forearc/syn-collisional Tso-jiangding Group [*Dürr*, 1996; *An et al.*, 2014; *DeCelles et al.*, 2014; *Orme et al.*, 2014], which lies on ophiolitic basement [*Hébert et al.*, 2012; *Wang et al.*, 2012; *Huang et al.*, 2015]. (3) The Indus-Yarlung Suture Zone (IYSZ) representing remnants of the Neo-Tethyan oceanic basin, consists of ophiolites and associated mélanges [*An et al.*, 2017], which is considered to have

formed in a MORB setting during the Jurassic and a supra-subduction setting during the Cretaceous [Malpas et al., 2003; Hébert et al., 2012; Maffione et al., 2015]. Maffione et al. [2015] also proposed that the Early Cretaceous supra-subduction ophiolites were formed within the forearc hyperextension processes, probably representing melting of subcontinental mantle of the Lhasa terrane. The IYSZ juxtaposes the Xigaze basin and Gangdese arc to the north and the Tethyan Himalayan to the south, marking the boundary between Asian and Indian plates prior to collision (Figure 1). The Yarlung Zangbo Mantle thrust (YZMT), which yields ^{40}Ar - ^{39}Ar cooling age of ~62-63 Ma, represents southward obduction of ophiolitic mélangé during early Paleocene [Ding et al., 2005]. The thrust was located on the southern margin of ophiolitic assemblage and was later partially buried by the Latest Oligocene to Early Miocene thrusting along the GCT (Figure 2).

(4) The Tethyan Himalaya mainly comprise Cambrian–Eocene low-grade metasedimentary and sedimentary rocks which were deposited along the passive margin of northern India [e.g. Liu and Einsele, 1994; Jadoul et al., 1998; Wan et al., 1998; Garzanti et al., 1999; Ding et al., 2005], as well as an East-West zone of the Cenozoic Northern Himalayan Gneiss domes [NHGD; e.g. Lee et al., 2004, 2007; Zeng et al., 2011; Pullen et al., 2011].

(5) The Greater Himalaya mainly consists of Proterozoic and Paleozoic high-grade metamorphosed metasedimentary rocks locally intruded by Early Paleozoic and Cenozoic granitoids [Parrish and Hodges, 1996; Yin and Harrison, 2000; McQuarrie et al., 2013].

(6) The Lesser Himalaya mainly comprises Proterozoic–Paleozoic metasedimentary rocks, metavolcanic and gneiss, overlain by Permian to Cretaceous strata which are similar to the Tethyan Himalayan sequence [e.g. Yin, 2006; DeCelles et al., 2014; references therein].

[6] Recently, it has been demonstrated that the foreland basin system developed along the entire Himalaya orogeny from the IYSZ to present Gangetic foreland basin. Based on studies from the Sangdanlin section in Saga (Figure 1) combined with previously published data from the IYSZ [Li *et al.*, 2015b], northern Tethyan Himalaya [Ding *et al.*, 2005; Hu *et al.*, 2016b] and frontal Nepalese Lesser Himalaya and Sub-Himalaya [DeCelles *et al.*, 2014], from Paleocene to the present this basin system experienced a flexural wave southward migrating ~1400 km across the Himalayan thrust belt.

3 Sedimentology and structure in the Xigaze basin

[7] This work concentrates on the Xigaze forearc basin near Xigaze (Figure 2), which mainly preserves the Aptian-Coniacian (~125-80 Ma) Chongdui and Ngamring Formations [Wang *et al.*, 2012; Orme *et al.*, 2014; Orme and Laskowski, 2016; Figure 3], as well as a small suit of upper Aptian to lower Albian carbonate, Sangzugang Formation, discontinuously exposing in the northern part of the forearc basin [Liu *et al.*, 1988; An *et al.*, 2014]. The Chongdui Formation was originally named by Cao [1991], and comprises greenish-purplish upper Barremian and upper Aptian radiolarian chert [Ziabrev *et al.*, 2003], interbedded with tuffaceous layers dated at ~119 - 114 Ma [Huang *et al.*, 2015; Wang *et al.*, 2017], overlain by grey thin-bedded sandstone, mudstone and limestone (a youngest age of ~116 Ma for detrital zircon U-Pb analyses reported by Wu *et al.*, 2010; interbedded tuffs with ages of ~113-110 Ma; Wang *et al.*, 2017). Later, this formation was redefined [An *et al.*, 2014], as only including the lower part: greenish-purplish radiolarian chert intercalated with greenish shale and calcilutite, which is considered to have been deposited over oceanic crust at abyssal depths (Figure 4). The Ngamring Formation overlying conformably the Chongdui

Formation (Figure 4) comprises several upward-fining turbidite interlayered with conglomerates [Wang *et al.*, 2012; Orme and Laskowski, 2016]. The depositional age of this Formation is still under debate, but biostratigraphic studies [Wan *et al.*, 1998; Li *et al.*, 2010] and detrital zircon U-Pb analyse constraints [e.g. Wu *et al.*, 2010; An *et al.*, 2014; Orme *et al.*, 2014; Orme and Laskowski, 2016] indicate its depositional age ranges from ~107 to 83 Ma during the Aptian–Turonian. Provenance analysis indicates that the major sediments of the basin were derived from the Gangdese arc [e.g. Dürr, 1996; Wu *et al.*, 2010; Orme *et al.*, 2014]. A >5 m thick conglomerate (Figures 2B, 3, 4-A4) within the middle part of the Ngamring Formation located in the southernmost basin has been interpreted to be deposited in a deep-water channel [Wang *et al.*, 2012; Orme *et al.*, 2014].

[8] Further, those upper Xigaze basin sequences, exposed in the Zhongba-Saga area (Figure 1), named the Tso-jiangding Group, includes Jialazi, Quxia, Qubeiya, and Padana formations, range in age from ~83 to 50 Ma [e.g. Wang *et al.*, 2012; An *et al.*, 2014; Orme *et al.*, 2014; Hu *et al.*, 2016b]. This group mainly comprises limestone, interbedded marine sandstone, shale and conglomerate, indicating a transition between the deep and shallow marine environment [Orme *et al.*, 2014; An *et al.*, 2014], which formed part of an Early Cenozoic syn-collisional basin system developed along the IYSZ [e.g. Ding *et al.*, 2005].

[9] In the study area, the Cretaceous sequence, is bounded by the Great Counter thrusts (GCT), which comprises two strands in the study area (i.e. on both the northern and southern basin boundaries, see Figure 2), forming a wide, asymmetric synclorium striking W-E, with a 6–8 km wide southern flank and a 10–15 km wide northern flank [Wang *et al.*, 2012; Figure 2]. The northern GCT defines the boundary between the preserved Xigaze basin

sequences and the Kailas Group, specifically the Qiuwu-Dazhuka Formation [Wang *et al.*, 2013; Li S. *et al.*, 2017; Figures 2, 4], extending to the east (Zedang, Figure 1) active during ~19-15 Ma [Quidelleur *et al.*, 1997; Harrison *et al.*, 2000] and to the west (Kailas, Figure 1) active between ~20-13 Ma [Yin *et al.*, 1999]. Furthermore, Carrapa *et al.* [2014] suggested the northern strand of the GCT (Figure 2) probably ceased to be active ~17 Ma. The southern GCT preserves an imbricated thrust, comprising from north to south the Xigaze basin sequences, Liuqu Formation, Xigaze ophiolite and the Northern Tethyan Himalaya sequences structurally overlying one another (Figures 2, 4). Based on strain analysis and restored sections, Einsele *et al.* [1994] proposed that the preserved basin segment had been shortened 65% of the original width from at least 65 km. Two Upper Oligocene-Miocene conglomerates lie on the northern and southern boundaries of the Xigaze basin, the Kailas Group, specifically the Qiuwu-Dazhuka Formation to the north [Wang *et al.*, 2013; Li S. *et al.*, 2017]; and the coeval Liuqu Formation to the south [David *et al.*, 2002; Li *et al.*, 2015a; Leary *et al.*, 2016; Figures 2, 4].

4 Sampling and methods

[10] Nine sandstones and a felsic dyke (T13-20), were sampled along a N-S transect of the Xigaze forearc basin (mainly Chongdui and Ngamring Formations) as well as a sandstone sample from the adjacent Qiuwu-Dazhuka Formation (Figure 2; the same transect studied for biostratigraphy by Wan *et al.*, 1998, sedimentation and structure by Einsele *et al.*, 1994 and Wang *et al.*, 2012). U-Pb zircon analyses were carried out to determine the maximum depositional age of sediments, as well as the age of felsic dyke emplacement. Furthermore, low-T thermochronology data were used to elucidate both the burial and

exhumation history of the basin. Sample T12-66, located near the core of synclinorium, is from the youngest strata in the preserved section of the Xigaze forearc basin sequence (Figure 2), while sample T13-22 is from the Qiuwu-Dazhuka Formation.

[11] To constrain the depositional ages of these sequences, we carried out detrital zircon U-Pb analyses, using an Agilent 7700 quadrupole inductively-coupled-plasma-mass-spectrometer with a 193 nm ArF Excimer laser at the School of Earth Sciences, The University of Melbourne. Details of the experimental method used are described in the Appendix [Woodhead *et al.*, 2007; Hellstrom, 2008; Paton *et al.*, 2010].

[12] Low-T thermochronology methods, e.g. AFT, AHe and ZHe, have different ranges of temperature sensitivity, termed the partial annealing/retention zone (AHe: ~40–80 °C; AFT: ~60–120 °C; ZHe: ~130–200 °C), and can be applied to determine the rate and timing of cooling of geological units in the upper crustal environment [e.g. Gleadow *et al.*, 2002; Reiners *et al.*, 2005; Flowers *et al.*, 2009]. Samples in this study were crushed and treated by traditional mineral separation techniques (heavy liquid and magnetic separation) to separate the apatite and zircon grains. AFT, AHe, and ZHe analyses were conducted on samples at the University of Melbourne. Details of these low-T thermochronology analytical procedures are described in the supporting information [Farley *et al.*, 1996; Flowers *et al.*, 2009; Gleadow *et al.*, 2009, 2015]

5 Results

5.1 U-Pb detrital zircon chronology

[13] In total, 696 subhedral or rounded zircon grains (80 to 250 μm) from six samples were analysed for constraining the depositional ages of the Xigaze forearc basin sequences,

which yielded 645 concordant U-Pb ages (Figure 5 and supplementary data). The southernmost sample T12-59 yielded 87 concordant U-Pb ages ranging between 3427–105 Ma. The youngest age group (14 grains) falls between ~107-105 Ma with a weighted mean age of $\sim 106 \pm 0.8$ Ma (Figure 5), providing a maximum depositional age constraint for the lower part of the Ngamring Formation. Sample T12-60 yielded 101 concordant ages ranging from ~3260 to 101 Ma with a youngest age peak of $\sim 102 \pm 0.9$ Ma (8 grains), from the slightly younger sequence of lower part of the Ngamring Formation. Sample T12-61 yielded 118 concordant ages ranging from 2260 to 97 Ma with a youngest age peak of $\sim 98.8 \pm 1.1$ Ma (5 grains), while sample T12-65 yielded 111 concordant ages ranging from 2157 to 90 Ma with a youngest age peak of $\sim 90.5 \pm 1.5$ Ma (4 grains). Sample T12-66 from the youngest sequence (synclorium core) yielded concordant ages of 3281-82 Ma with youngest age peak of $\sim 82.9 \pm 1.0$ Ma (4 grains), while sample T13-19-1 from the northern flank yielded 115 concordant ages in range of 2733-93 Ma with a youngest age peak of $\sim 94.2 \pm 0.8$ Ma (7 grains). Worthy of note is that in sample T12-61 the youngest detrital U-Pb age measured is $\sim 98.8 \pm 1.1$ Ma (see supplementary data), which is slightly older than the previous biostratigraphic Turonian age for this strata [Wan *et al.*, 1998]. This implies that there may be slightly younger zircons in this unit that have not been recorded in our analyses (Figure 3). Generally, the youngest peaks of detrital U-Pb ages from these samples show a younging trend of the sedimentary sequences from the northern and southern flanks to the synclorium core (Figure 3), consistent with previous biostratigraphic study [Wan *et al.*, 1998]. Furthermore, sample (T13-20) from the felsic dyke on the northern flank, has a concordant zircon U-Pb age of $\sim 14.84 \pm 0.11$ Ma (Figure 6).

5.2 AFT data

[14] Eleven samples were analysed for AFT using the 'RadialPlotter' (Figure 7; Vermeesch, 2009) and each only displays one single age peak, which is always considerably younger than its age of deposition (Figures 3, 5). AFT pooled ages of eight sedimentary rocks from the N-S transect (N-S) in the Xigaze forearc basin range from $\sim 62.6 \pm 3.2$ to $\sim 16.3 \pm 1.5$ Ma, and generally show a pattern of northward younging (Figure 7). Slightly older ages in samples T13-19-1 and T13-19-2 at higher elevation (>4200 m) compared to samples T12-65 and T12-66 located in close proximity, but at slightly lower elevations (around 4000 m), is probably a result of earlier cooling of the higher elevation samples (Table 1). The relatively short track lengths ranging between 10.8-11.9 μm for the mean length (Table 1), showing that these samples were buried within the partial annealing zone of AFT or reheated for a long period before exhuming to the near surface environment. The AFT age of $\sim 15.0 \pm 1.0$ Ma from sample T13-22, collected from the Late Oligocene-Miocene Qiuwu-Dazhuka Formation, is consistent with data previous published previously from the same unit located near Kailas [Carrapa *et al.*, 2014]. The felsic dyke sample (T12-20), yielded a pooled AFT age at $\sim 15.0 \pm 2.0$ Ma, comparable (within analytical error) with the coexisting zircon U-Pb age of $\sim 14.84 \pm 0.11$ Ma (Figure 6).

5.3 AHe data

[15] A total of 21 grains from six samples (2-4 grains for each sample) were analysed for AHe dating, which have [eU] values ranging from 2.3 to 55.1 ppm (Table 2) without clear relationships between their ages and [eU] (see Figure S1 in the supplements). All grains

yielded reproducible Miocene AHe ages, ranging between $\sim 15.0 \pm 1.1 - 7.7 \pm 0.5$ Ma (Table 2), considerably younger than their own corresponding AFT and depositional ages. Samples T12-65 and -66 at lower elevations, from the youngest strata near the core of the synclorium at ~ 3900 m, yielded the youngest AHe ages of 7.7 ± 0.5 and 8.2 ± 2.3 Ma, respectively, whereas other samples located on the flanks at slightly higher elevations (~ 4000 - 4700 m), yield slightly older ages (Tables 1 and 2).

5.4 ZHe data

[16] Six sandstones samples (T12-59, -60, -61, -62, -65 and T13-19-1) from Xigaze forearc basin strata as well as sample T13-22 from the Qiuwu-Dazhuka Formation were selected for ZHe dating. 3-7 grains were analysed for each sample (28 grains in total) and most grains have relatively low [eU] values, < 700 ppm, except for one grain (1225 ppm) of sample T13-22 (Table 3). However, this high [eU] grain, which might be expected to show the effects of enhanced He diffusion [Guenther *et al.*, 2013] yielded an age of $\sim 17.3 \pm 1.1$ Ma. Considering the analytical error, this is concordant with ages of other grains from sample T13-22 (Table 3). Sample T12-59 yielded seven dispersed ZHe ages in range of $\sim 89.8 \pm 5.3 - 57.3 \pm 3.6$ Ma, while sample T12-60 yielded five dispersed ZHe ages falling between $\sim 92.5 \pm 5.7$ and 53.4 ± 3.3 . The single grain ages of the two samples are all younger than their depositional ages, indicating they were partially reset. A further four samples from the Xigaze forearc basin yielded reproducible ages from Late Cretaceous to Early Miocene, with weighted mean ages in the range of $\sim 72.0 \pm 6.7 - 24.6 \pm 1.8$ Ma, while a sample (T12-22) from Qiuwu-Dazhuka Formation yielded an age of $\sim 18.0 \pm 1.3$ Ma (weighted mean age; Table 3).

[17] In general, AFT, AHe and ZHe ages from the sandstones are all significantly younger than their depositional ages and are considered to have been totally reset following deposition, except for the ZHe ages for the two southernmost samples (T12-59 and 60), which are considered to have been only partially reset (Figures 3, 5 and Tables 1, 2, 3). These low-T thermochronology age data are consistent with their different expected temperature sensitivities, $ZHe > AFT > AHe$. The spatial and temporal distributions of the ZHe and AFT ages show a similar northward younging pattern, while AHe results from samples consistently yield Miocene ages (Figure 8). This pattern prevails despite samples having been located at different elevations ranging from 3900 to 4700 m, hence their ages are considered to have been mainly controlled by their location within the basin. Of note is that the four samples from the narrow southernmost basin area (~5-6 km wide) yield pre-Oligocene ZHe and AFT ages, while all others to the north all yield Miocene ages.

6 Thermal history modelling

6.1 Modelling strategy for single samples

[18] Based on our AFT, ZHe and AHe data and some regional geological constraints, the thermal histories for eight samples were modelled together, employing the inverse method of the HeFTy software [Ketchum, 2005, 2007]. Two initial geological constraints are applied for these thermal history modelling: (1) the temperature of 15 ± 5 °C for the mean present surface; (2) Our new detrital zircon U-Pb ages (the youngest age peaks) and biostratigraphy study published by Wan *et al.* [1998] are used to constrain depositional ages of samples from the Xigaze basin sequence, while the crystallization age was used for igneous sample T13-20.

[19] Samples T12-59, 61, 62, 65 and T13-19-1 were modeled using combined ZHe, AHe and AFT data; the sample T12-66 was modeled with AHe and AFT data using constrains from ZHe ages of its nearby sample T12-65. AFT data from sample T12-60 was combined with the AHe age of nearby sample T12-59, while sample T13-20 was modeled using AFT data with constraints from its zircon U-Pb age (Figure 6). For samples T12-59 and -60, for ZHe data broad constraint boxes were used for because of partial resetting for ZHe system (Figure 9). The further modelling strategy is described in details in Appendix [Ketcham *et al.*, 2007].

6.2 Results of thermal history modelling

[20] Thermal history models of the low-T thermochronology data show that the timing of onset of cooling propagated from south to north (Figures 9, 10). In the south, Early Cretaceous sediments underwent pronounced cooling between $\sim 89 \pm 2$ and 80 ± 3 Ma (samples T12-59, -60, located on the southernmost part of the basin; Figure 2), followed by a lengthy slow cooling period until Early Miocene time. Samples T12-61 and -62 (Cenomanian), located further north, show rapid cooling over an interval from $\sim 65 \pm 3$ to 52 ± 3 Ma, followed by slow cooling through to Early Miocene time. By contrast, four samples (T12-65, -66, T13-19-1 and -2, Turonian-Santonian) from the central and northern Xigaze basin, experienced a prolonged heating history through to latest Eocene time ($\sim 34 \pm 3$ Ma), followed by rapid Oligocene cooling (Figures 6, 7). All samples record pronounced cooling commencing in the Middle Miocene ($\sim 14 \pm 2$ Ma; Figures 9, 10). Note that pre-Oligocene cooling episodes are only recorded by samples located on the narrow southern basin flank.

7 Discussion

7.1 Time span of the Xigaze basin

[21] Currently, the Xigaze basin sequences expose two types of deposits: the forearc and overlying syn-collisional basin sequence along the Indian-Asian collisional zone. These sedimentary archives record the processes of pre- and syn- Indian-Asian collision. In the study area however, only the forearc sequences consisting of the Aptian (~113 to 110 Ma) Chongdui Formation without the radiolarian chert unit [An *et al.*, 2014; Huang *et al.*, 2015; Wang *et al.*, 2017] and Albian - Santonian (~110 to 83 Ma) Ngamring Formation (Figure 3), have been preserved. Our new U-Pb zircon data from the Ngamring Formation generally support previous studies on the deposition age of the Xigaze forearc sequences near Xigaze (Figures 3 and 5). To the west, the younger deposits, known as the Campanian to Ypresian (~82 to 50 Ma) Tso-jiangding Group, have been preserved in the Zhongba-Saga areas (Figure 1). Based on recent studies, the initial India-Asia collision probably occurred at ~60 Ma [e.g. DeCelles *et al.*, 2014; Hu *et al.*, 2015, 2016a]. In this case, the later sequence in Xigaze basin could be defined as a collision-related syn-collisional basin [Hu *et al.*, 2016], currently mainly including the youngest unit, the Lower Eocene Jialazi Formation near Zhongba which consists of the limestone interlayered with thin sandstone and conglomerate sequences [e.g. Orme *et al.*, 2014; Hu *et al.*, 2015, 2016a]. The preservation of Eocene strata provides evidence that deposition in the basin continued after initial collision.

[22] Furthermore, recent low-temperature thermochronology studies indicate that a considerable section was removed from the entire India-Asia collisional zone during Miocene [Caparra *et al.*, 2014; Li *et al.*, 2015a, c]. Hence, Eocene strata were probably deposited over the entire Xigaze basin. Because the basin form is a gentle syncline with no record of

significant Eocene structural activity, the heating observed in thermal history models is probably attributed to continued sedimentary accumulation caused by the northward migration of the basin depocenter until latest Eocene time, rather than by folding and/or faulting. The termination of heating is coeval with the last recorded regional marine sedimentation to the south in Yadong [Jiang *et al.*, 2016], as well as in Gyangze (Li *et al.*, 2005; although the timing of this marine sequence is still under debate; Figure 1), which probably indicates that in southern Tibet the remnant Neo-Tethyan Sea finally terminated at that time. Thus, we propose that deposition in the Xigaze basin continued until latest Eocene or earliest Oligocene time, and that the upper sequence was subsequently eroded.

7.2 Cooling and exhumation history of the Xigaze basin

[23] As mentioned above, samples with pre-Oligocene apparent ZHe and AFT ages and cooling episodes are only located in a narrow zone along the southern basin margin, while others (located in the central and northern part) all show Miocene ages and Oligocene-Miocene cooling. This spatial pattern in the cooling/exhumation history is attributed to the early geometrical architecture of the Xigaze basin during its deposition. Recently, Noda (2016) reviewed characteristics of present day compressional forearc basin systems that have an asymmetric 'listric' geometry and developed through landward migration of the basin depocenter. We propose a similar structural model for the Xigaze basin with a 'listric' geometry and landward migrating depocenter during Late Cretaceous (Figure 11). This model is also consistent with its present asymmetric synclorium profile (Figure 2B). Further, the termination of post-depositional heating propagating from south to north is also considered to correlate with northward migration of the Xigaze basin depocenter (Figure 11).

[24] In detail, the temporal record of cooling in the Xigaze basin correlates with significant, independently constrained observations, relevant to the developing collision dynamics. The onset of cooling (at $\sim 89 \pm 2$ and 80 ± 3 Ma) in the southernmost basin was accompanied by thrusting (probably representing early activity of the YZMT, *Ding et al.*, 2005) or uplift of the accretionary wedge and ophiolites along its southern margin. We relate this uplift/exhumation episode with accelerated northward convergence and anticlockwise rotation of the Indian plate relative to Asia between ~ 90 and 80 Ma, which has been attributed to Morondova LIP activity and drag of Neo-Tethyan slab subduction [*van Hinsbergen et al.*, 2011, Figure 10]. Acceleration and rotation of India led to a changing pattern of Neo-Tethyan slab subduction and/or possible regional stress during that time, which triggered thrusting of the accretionary wedge and ophiolitic basement and exhumation of the southernmost Xigaze basin. Further, the occurrence of the unconformable conglomerate layer in the southern basin (Figure 4-A4), is a response of this period of exhumation in the southernmost portion, although it was previously interpreted as a deep water channel [*Wang et al.*, 2012].

[25] Further north, the cooling episode from $\sim 65 \pm 3$ to 52 ± 3 Ma also coincided with a period of the fastest India-Asia convergence possibly linked to activity of the Deccan LIP and traction of fast Neo-Tethyan subduction [*van Hinsbergen et al.*, 2011; Figure 10]. Similar to the earlier exhumation described above, this second episode is attributed to continued thrusting along the YZMT [*Ding et al.*, 2005], resulting in propagation exhumation further north within the basin. Subsequent slow cooling probably relates to the significant decrease in convergence that accompanied ongoing India-Asia collision. Based on sedimentary

provenance analysis, *Hu et al.* [2015, 2016a] and *DeCelles et al.* [2014] argued for initial collision in southern Tibet at $\sim 59 \pm 1$ Ma. However, no significant decrease of the convergence rate is apparent at that time, possibly due to accommodation by subduction of the Indian lithosphere and 'softer' upper crustal shortening.

[26] In the central and northern basin, continuous heating revealed by our thermal modeling is attributed to continued sedimentary accumulation in the basin until latest Eocene time. The subsequent pronounced Oligocene cooling, probably linked to the crustal flexure, was related to Indian slab high-angle subduction or tearing [*Zhang et al.*, 2014]. This was also accompanied by a period of slightly accelerated Indian convergence (Figure 10). Later slow to minimal Early Miocene cooling was probably associated with the proposed decrease in subduction angle of the Indian slab following its break-off as recorded by contemporary ultrapotassic magmatism in southern Lhasa [*Tian et al.*, 2017; Figure 10]. This cooling pattern coincides with a slightly decrease in the India-Asia convergence at that time [~ 25 -15 Ma, *van Hinsbergen et al.*, 2011a].

[27] In keeping with previous regional findings (Figure 1), for example, Kailas area [*Carrapa et al.*, 2014], the southern Gangdese belt [*Copeland et al.* 1997; *Dai et al.*, 2013; *Tremblay et al.*, 2015; *Li et al.*, 2016; *Ge et al.*, 2017], Liuqu Formation [*Li et al.*, 2015a] and Zedang area in southeast Tibet [*Li et al.*, 2015c], all apatite samples analysed here show pronounced cooling since Middle Miocene time (Figures 9, 10). The modern Yarlung River system has also been incising the IYSZ at least since that time [*Cina et al.*, 2009; *Lang et al.*, 2014]. Hence, the Miocene cooling phase is here attributed to of the post-thrust (GCT) erosion and Yarlung River incision.

[28] Recently, low-T thermochronology data (e.g. ZFT, AFT, ZHe and AHe) were reported by *Dai et al.* [2013] and *Ge et al.* [2017] from the Gangdese batholith near Xigaze located to the north of this study area. They suggested that the northern Gangdese batholith (from N29.5° to the north) experienced Late Eocene–Early Oligocene exhumation, which might have been triggered by crustal thickening followed by the Neo-Tethyan slab breakoff. By contrast, the southern Gangdese batholith only recorded the Late Oligocene–Early Miocene fast cooling, which may be a result of denudation related to the Late Oligocene Gangdese Thrust or regional extension. By the Early Miocene, the rapid exhumation is considered to have associated with localized Yarlung river incision [*Li et al.*, 2016; Figure 1]. Therefore, it appears that the exhumation/cooling history of the Xigaze basin differs from that of the Gangdese arc to the north. We propose that the Xigaze basin is a relatively ‘soft’ unit, located within the collision zone, and was therefore more sensitive to the effects of India-Asia convergence (e.g. thrusting and/or folding), compared to the more distal and relative ‘rigid’ Gangdese batholith further north.

7.3 Implication for evolution of India-Asia convergence

[29] In summary, our study shows that the geological evolution of the Xigaze basin between Early Cretaceous (~113 Ma) and latest Eocene (~34 Ma) time carries a unique record of both forearc and syn-collisional basin systems in the course of the India-Asia convergence. To the south, the Indian plate initially separated from eastern Gondwana (Australian continent) at ~132 Ma (Early Cretaceous), in response to activity of the Cuomei-Bunbury LIP [*Zhu et al.*, 2013] and demonstrated by marine magnetic anomalies [*Muller et al.*, 2008]. To the north, the Xigaze forearc basin was initially deposited on oceanic crust

adjacent to the southern Asian continental margin, fed by increasing volumes of Gangdese arc-derived sediments (Figure 12A). From ~90 Ma, acceleration of the northward movement and rotation of the Indian plate triggered rapid thrusting of the underlying accretionary wedge and ophiolites. This resulted in exhumation/uplift of the southernmost part of the basin at that time and was accompanied by northward movement of its depocenter (Figures 10, 12B). The Gangdese arc also records a strong magmatism at that time which is related to Neo-Tethyan subduction [*Ji et al.*, 2009].

[30] In the early Paleocene, the high convergence rate between the Indian and Asian plates from ~65 to 50 Ma led to a further episode of uplift of the southern basin and initial collision between India and Asia occurred. This resulted in extensive shortening (by folding) of the sedimentary sequences (Figure 12C), and deceleration of the Indian plate is only recorded after ~50 Ma, following this 'soft collision' stage. Since then, dramatically decreased the convergence rate between India and Asia was accompanied by activity of the Tethyan Himalayan fold-thrust belt [*Ratschbacher et al.*, 1994; *Murphy and Yin*, 2003; *Ding et al.*, 2005] and high temperature metamorphism in Tethyan Himalaya commencing at ~50 Ma [*Lee et al.*, 2000; *Lee and Whitehouse*, 2007], as well as a coeval episode of Gangdese magmatism between ~60 and 45 Ma [e.g. *Ji et al.*, 2009, 2015; *Zhu et al.*, 2009]. Hence, this post ~50 Ma stage can be linked to later 'hard collision' related to continental crust collision [*Molnar and Tapponnier*, 1975; *Lee and Lawver*, 1995]. During this period, the Xigaze basin transitioned from a forearc to collision-related syn-collisional basin system in front of the Gangdese arc, and sediment sourced from the Gangdese arc along the south Asian margin was continuously transported into the Xigaze basin (Figure 12C, D), as well as to other foreland

basins further south [Renbu, Sangdanlin basins; *DeCelles et al.*, 2014; *Orme et al.*, 2014; *Li et al.*, 2015b; Figure 12C].

[31] Following Neo-Tethyan slab breakoff by ~45 Ma [*Replumaz et al.*, 2010; *Ji et al.*, 2016; Figure 9D], the Indian lithosphere flat subduction caused strong horizontal compression and deceleration of India-Asia convergence and contributed to formation and uplift of the central Tibetan Plateau [Qiangtang and Lhasa terranes in Figure 1; *Rohrmann et al.*, 2012; *Li et al.*, 2016]. This led to further development of crustal thickening of the Tethyan Himalaya [*Zeng et al.*, 2011; *Aikman et al.*, 2012], as well as southward migration of the foreland basin system. Sedimentation of the Xigaze syn-collisional basin finally terminated by $\sim 34 \pm 4$ Ma and the remnant Neo-Tethyan Sea in south Tibet finally closed.

[32] After latest Eocene time, with continued India-Asia convergence and increasing high-angle subduction and break-off of the India slab, the Xigaze basin experienced rapid uplift and erosion, leading to removal of the uppermost syn-collisional basin sequence. During the latest Oligocene-Early Miocene, two fluvial basins (Kailas and Liuqu) were formed in local structural depressions along the north and south boundaries of the Xigaze basin [Figure 12E; *Li et al.*, 2015b; *Leary et al.*, 2016]. At that time, the Xigaze ophiolite was exposed, and together with Xigaze basin strata, provided the source for the Liuqu Formation (to the south) and Kailas Group (to the north). In the Early Miocene, following Indian slab break-off, enhanced crustal uplift and shortening activated extrusion of the Himalaya (MCT and STD activities) and movement of the GCT [*Yin*, 2006], resulting in ophiolite thrusting over the Xigaze and fluvial basins. This led to cessation of sedimentation in fluvial basins, and also localised the modern Yarlung drainage system with accompanying widespread

denudation [Carrapa *et al.*, 2014; Li *et al.*, 2015c]. Furthermore, the Tibetan Plateau has been undergoing the E-W extension since the Miocene [e.g. Harrison *et al.*, 1992] and been being shaped by both tectonic and climatic forces (Figure 12F).

8 Conclusions

[33] In the study area, the Xigaze forearc/syn-collisional basin, preserves a unique record of Cretaceous and Cenozoic India-Asia convergence. Combining results of new U-Pb zircon data with previous studies, confirms that sedimentary units preserved in the Xigaze basin and studied here range in age from ~113 to 80 Ma and represent a forearc sequence.

[34] New low-T thermochronology data from a N-S section across the Xigaze forearc basin near Xigaze, generally show a northward younging age-trend, consistent with a northward propagating heating and cooling thermal history pattern. An early episode of cooling occurred in the southern basin from ~90 to 80 Ma and was followed by a later fast cooling episode between ~65-50 Ma; whereas the central and northern Xigaze basin experienced a longer burial history until the latest Eocene (~35 Ma). This burial represents a substantial collision-related sedimentary sequence deposited until ~35 Ma, which has since been removed, but is partially preserved in the basin at >300 km to the west.

[35] Late Cretaceous - Oligocene cooling/exhumation episodes recorded in the Xigaze basin relate to thrusting and folding associated with changes in India-Asia convergence rates. The later pronounced rapid Miocene cooling episode, which is widespread across the region, is related to post-thrust (GCT) erosion and incision by the Yarlung River. These temporal and

spatial relationships indicate that surface processes within the orogenic belt are strongly coupled with dynamic activity of the deep crust.

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Figure captions

Figure 1. Simplified geological map of the Himalaya orogeny (modified after Yin, 2006). The dark green dashed circle represents the location of the Cuomei LIP [Zhu *et al.*, 2013]; the leucogranites in Tethyan Himalaya (marked as a pink belt) formed the Northern Himalaya Gneiss Domes (NHGD, Zeng *et al.*, 2011).

Figure 2. (A) Geologic map of the Xigaze area with sample locations. (B) Structural cross section and sample locations along (N-S) (modified after *Einsele et al.*, 1994 and *Wang et al.*, 2012), in light of our field observations.

Figure 3. Stratigraphy of the Xigaze forearc basin near Xigaze modified after *An et al.* [2014], showing sample positions, low-T thermochronology data and minimum detrital zircon U-Pb age peaks (Ma) reported in this study. Alb = Albian, Apt = Aptian, Bar = Barremian, Con = Coniacian, Cen = Cenomanian, San = Santonian, Tur = Turonian.

Figure 4. Field features and lithologies of the Xigaze forearc basin and adjacent units. A, Southern Xigaze basin. View towards the west, showing contacts between the Xigaze ophiolite, Liuqu Conglomerate and Xigaze forearc sequence. A1: northward thrust in ophiolite body; A2: contact between ophiolite and Liuqu Conglomerate; A3: Chongdui Formation, showing location of sample T12-59; A4: 'Channel conglomerate' in the Middle part of the Ngamring Formation (southern basin) shown in Figure 2B. B. Location of samples (T13-19-1 and -2) in a syncline in central Xigaze forearc basin; C. northern Xigaze basin, thrust over latest Oligocene-Early Miocene Qiuwu-Dazhuka Formation, showing the location of sample T13-22.

Figure 5. Plots of detrital zircon U-Pb age probability from the Xigaze forearc sequence.

Figure 6. Weighted average of ^{206}Pb -corrected ages and concordia plot from sample T13-20. MSWD = Mean Square of Weighted Deviates.

Figure 7. Radial plots of the apatite FT ages using the RadialPlotter [Vermeesch, 2009].

Figure 8. Plot of thermochronology ages ($\pm 1\sigma$) for samples vs latitude along the transect S-N in the Figure 2. Dispersed ZHe ages for the two southernmost samples are not shown. GCT = Great Counter Thrust.

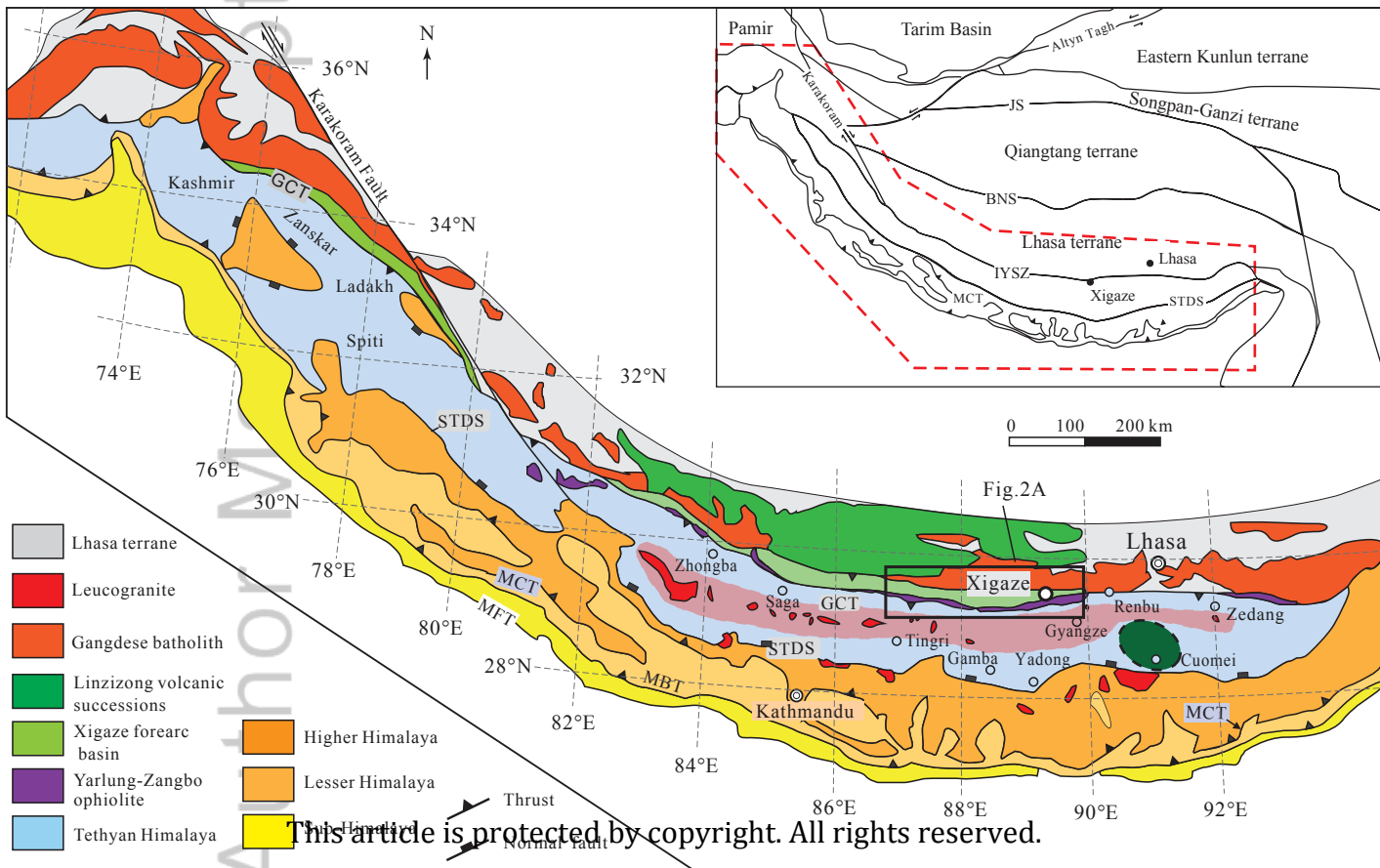
Figure 9. Thermal history modeling results of samples from the study area. Constraints are shown as black boxes. Left panel: ‘Good’ paths (GOF >0.55) shown as dark green envelopes and ‘acceptable’ paths (GOF >0.05) as yellow envelopes. The red line represents the weighted mean thermal path for all good models and a white line is the best-fit thermal path for each sample. Right panel: length distribution histograms (see legend for further details). GOF = goodness of fit.

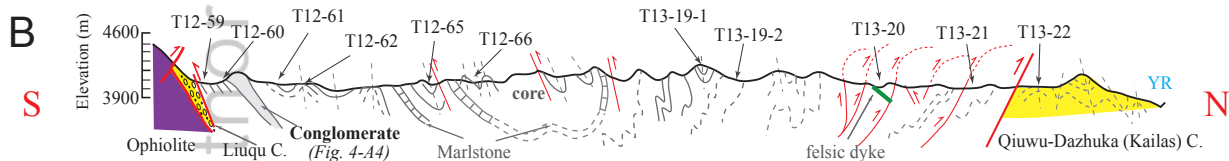
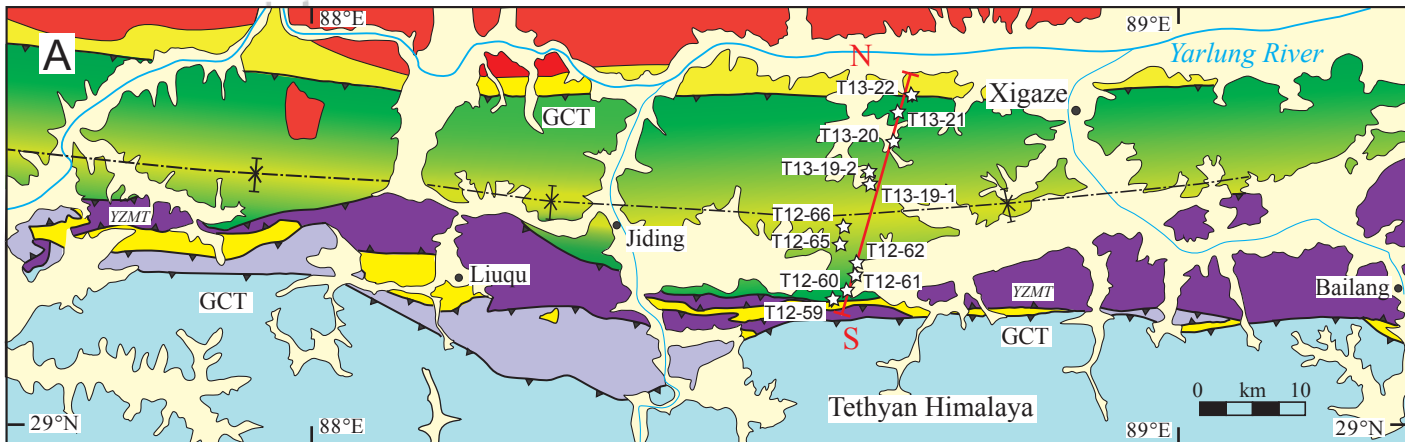
Figure 10. A. Weighted mean thermal paths for samples from the Xigaze basin (as shown in Figure 9) display a northward younging cooling trend. Grey bars mark the timing of onset of cooling episodes. B. Relative India-Asia convergent velocities of Eastern/Western Himalayan Syntaxis (E/WHS) from ~120 Ma to present [van Hinsbergen *et al.*, 2011a] showing timing of the Morondova and Deccan LIPs, Initial India-Asia collision [DeCelles *et al.*, 2014; Hu *et*

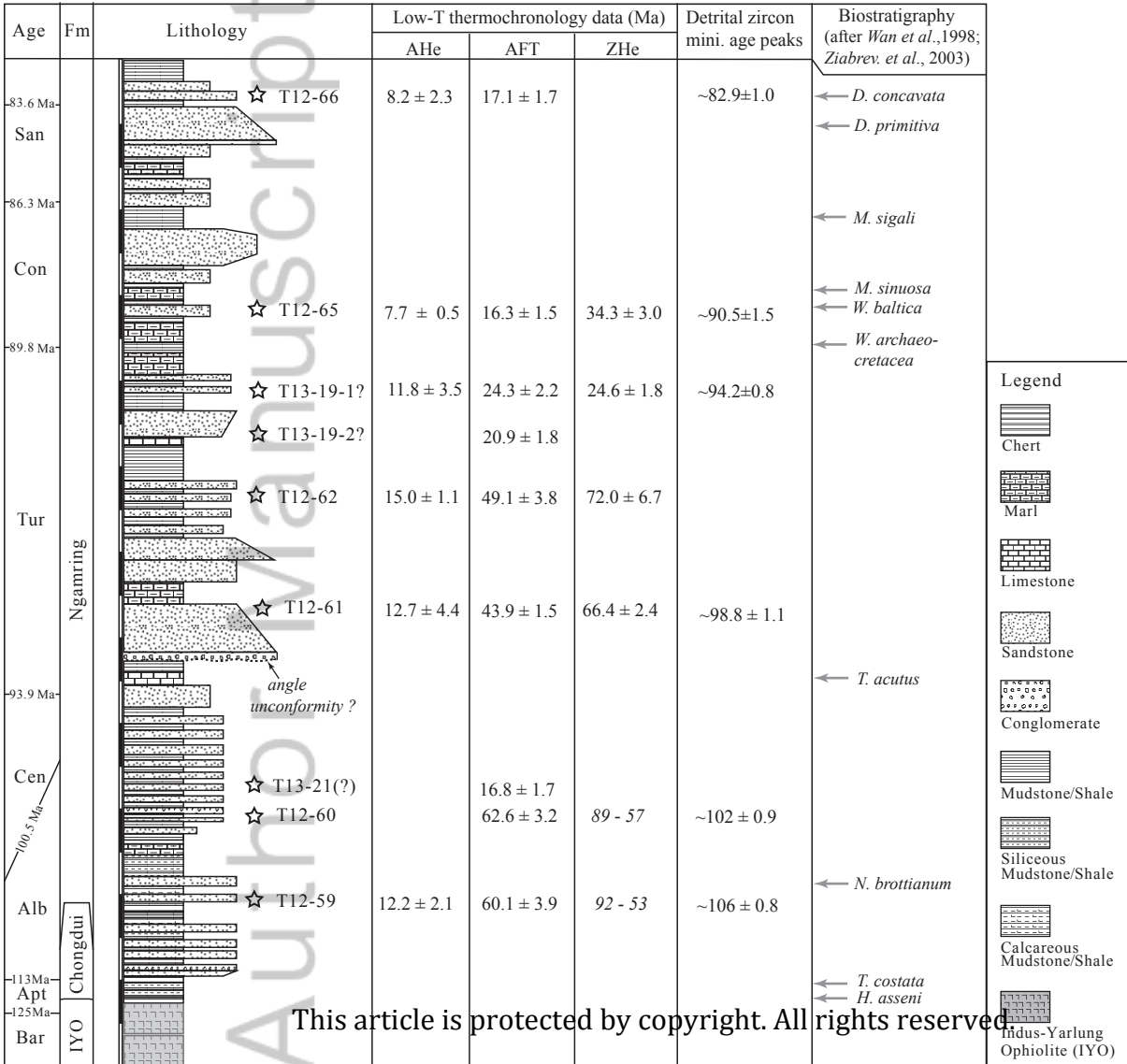
al., 2015], Neo-Tethys slab breakoff [*Ji et al.*, 2016], Indian slab tearing [*Zhang et al.*, 2014] and Indian slab breakoff reflected by ultrapotassic magmatism of the southern Lhasa terrane [*Tian et al.*, 2017]; LIP – Large Igneous Province.

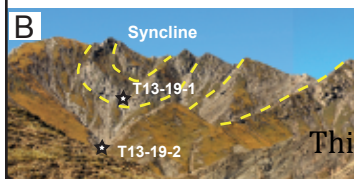
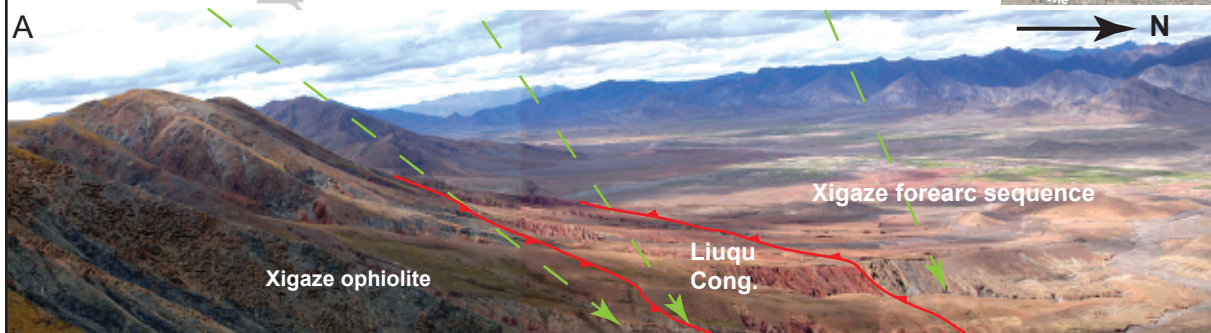
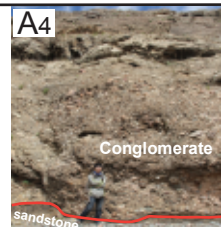
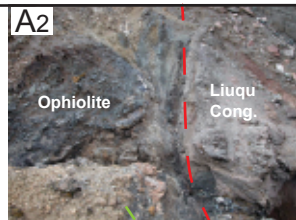
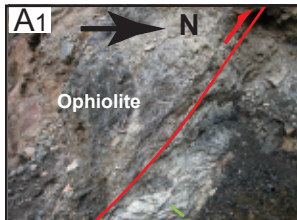
Figure 11. Tectonic model for southern Asian margin in Tibet during ~90-80 Ma. The Xigaze basin had an asymmetric listric geometry with northward migration of the depocenter (dashed circles), resulting in rapid exhumation of the southern basin, SSZ – Supra-subduction zone.

Figure 12. Schematic Early Cretaceous to present paleogeographic evolution of the Tibetan Plateau. The yellow bar in each panel represents the cross-section locations. GCT = Great Counter Thrust; GT = Gangdese Thrust; NHGD = Northern Himalayan Gneiss Domes; LIP = Large Igneous Province; SSZ = Supra-subduction zone; F./G. = Formation/Group; IC = Indochina; QK = Qaidam-Kunlun; QT = Qiangtang; SC = South China; SG = Songpan-Ganzi; Ta = Tarim.



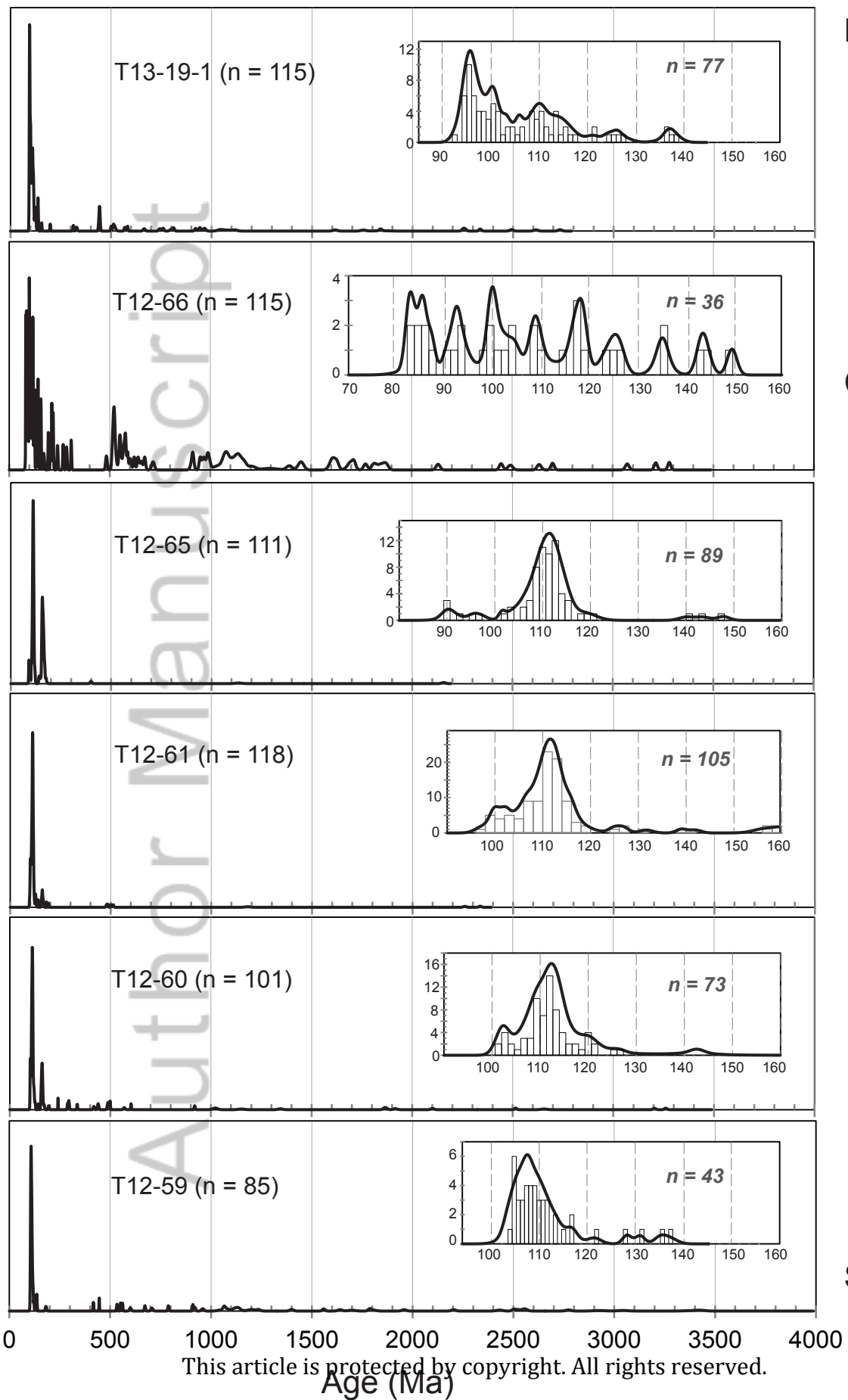


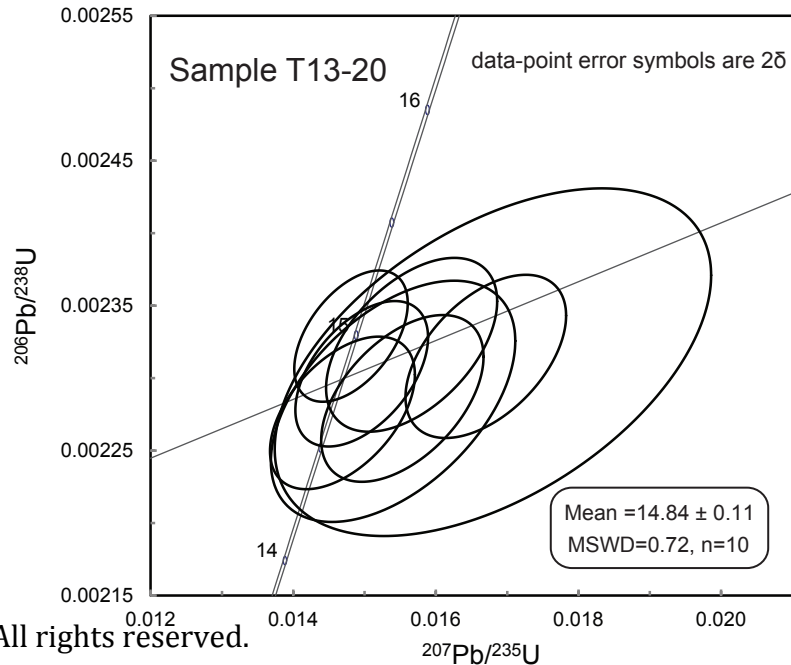
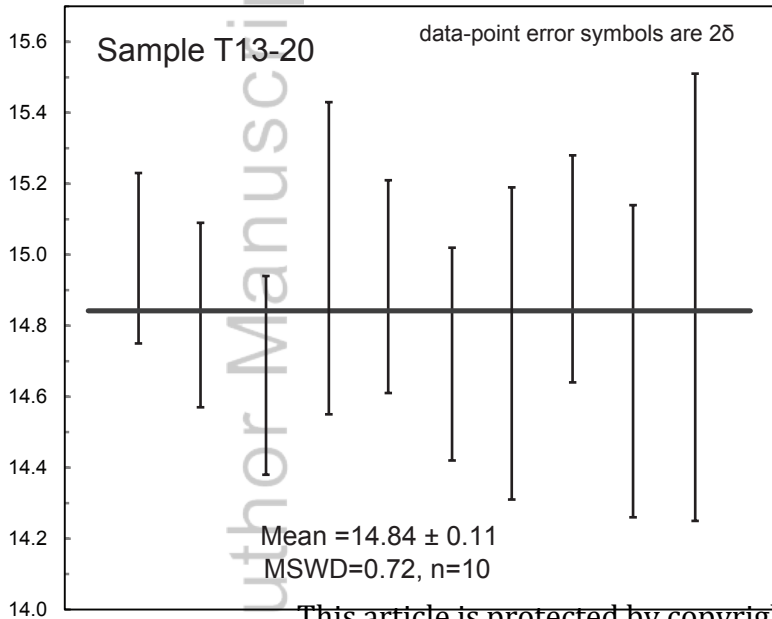




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Relative probability





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