Evidence of pre-Oligocene emergence of the Indian passive margin and the timing of collision initiation between India and Eurasia

Alka Tripathy-Lang[1], Kip V. Hodges[1], Matthijs C. van Soest[1], and Talat Ahmad[2,3]

[1]SCHOOL OF EARTH AND SPACE EXPLORATION, ARIZONA STATE UNIVERSITY, TEMPE, ARIZONA 85287, USA
[2]DEPARTMENT OF GEOLOGY, UNIVERSITY OF DELHI, DELHI 110007, INDIA
[3]UNIVERSITY OF KASHMIR, HAZARATBAL, SRINAGAR, J&K 190006, INDIA

ABSTRACT

Precise knowledge of the timing of Indo-Eurasian collision is prerequisite for understanding the subsequent evolution of the Himalayan-Tibetan orogenic system, yet the topic remains controversial despite decades of research. We present new data for the Upper Oligocene Basgo Formation of the Indus Basin of NW India that specifically address the proposal that collision initiated no earlier than the Eocene-Oligocene boundary. The Basgo Formation has been cited as the base of the Indus Group because of its previously assumed Maastrichtian age. This age has been revised to Upper Oligocene, but the stratigraphic location has not been re-evaluated. As such, it has been used as evidence of Oligocene-aged collision between India and Eurasia. Based on age constraints in the remainder of the Indus Group, we revise the stratigraphy and place it instead toward the top of the succession. We present evidence that the zircons in the Basgo sandstones originated from the Indian passive margin. Because conglomerate clasts are known to come from the Transhimalayan batholith to the north, our data support mixed provenance and require a minimum late Oligocene age for India-Eurasia collision in the NW Indian Himalaya. (U-Th)/He cooling dates for detrital zircons from the Basgo Formation range from 52.6 to 28.25 Ma, however, implying that their most probable source, the Indian passive margin, was emergent and eroding prior to Oligocene time due to collision. These data alone do not speak to whether the Basgo Formation records pre-Oligocene collision of India and Eurasia or India and the Transhimalayan Ladakh batholith, but as of the date of this publication, there is no evidence for Oligocene collision anywhere else in the Ladakh region. Thus, we interpret our data to demonstrate terminal collision between India and Eurasia prior to Oligocene time.

INTRODUCTION

The collision between India and Eurasia was a profound geodynamic event that, beyond building the Himalayan-Tibetan orogenic system, has affected regional—and possibly global—climate patterns (e.g., Raymo and Ruddimann, 1992). However, the timing of initiation of this event remains controversial despite years of research on the topic. Popular estimates range from Maastrichtian to early Oligocene (e.g., Yin and Harrison, 2000; Aitchison et al., 2007), and no consensus regarding whether the initiation of collision was diachronous has been reached (Rowley, 1996; Zhang et al., 2012).

Proponents of a Late Cretaceous collision are most strongly persuaded by paleontological evidence of Maastrichtian terrestrial faunal exchange between India and Eurasia (Jaeger et al., 1989), and the oft-cited Eocene collisional age is considered strictly a minimum because the amount of India subducted beneath Eurasia is unknown (Yin and Harrison, 2000). However, other researchers (e.g., Aitchison et al., 2007) interpret several observations to imply an early Oligocene collision. Examples include an apparent decrease in northward motion of India at 20 Ma (Acton, 1999), Oligocene to Miocene uplift and unroofing of the Transhimalayan batholiths (e.g., Kirstein et al., 2009), and late Oligocene–Miocene movement along major Himalayan fault systems (e.g., Hodges, 2000, and references therein). Other lines of reasoning are disputed, such as cessation of marine sedimentation in the Zephure Shan area near Mount Everest, where Wang et al. (2002) claim that the last marine limestone is Lutetian, and overlying noncarbonate marine sediments are as young as Priabonian, placing collision at ca. 34 Ma. In the same region, Zhu et al. (2005) counter that the same limestone and immediately overlying units are Ypresian, thus placing collision at ca. 50.6 Ma. To verify which findings were correct, Aitchison et al. (2007) revisited the same locality and confirmed the study of Wang et al. (2002), although these data were not published. Najman et al. (2010) also visited and confirmed the findings of Zhu et al. (2005), which lend more weight to an Eocene age of collision. Another disputed line of evidence used to argue for Oligocene collision is the presence of late Oligocene to early Miocene conglomeratic intermontane basins along the Indus-Tsangpo suture zone (Aitchison et al., 2002; DeCelles et al., 2011). However, there are older conglomeratic intermontane basins elsewhere, with the Indus Basin being a prime example (e.g., Henderson et al., 2010). An argument for Oligocene calc-alkaline magmatism (e.g., Chung et al., 2005), implies continued subduction until then, (Aitchison et al., 2007), although the geochemistry of such magmas is not always diagnostic of tectonic setting (Najman et al., 2010). Proponents of young collision also point to the small amount of pre-Oligocene orogen-derived clastic detritus in the Himalayan foreland as further evidence against continent-continent collision beginning prior to Oligocene time (Aitchison et al., 2007), although this argument discounts the large amount of pre-Oligocene sediment in depocenters like the Katawaz Basin, Makran accretionary complex, and Inner Burman Basin (Rowley, 1996). Finally, a particularly controversial point focuses on the paleolatitude of India at 55 Ma, as derived from paleomagnetic

data. Aitchison et al. (2007, their fig. 5) placed India many hundreds of kilometers south and east of Eurasia, whereas Najman et al. (2010, their fig. 9) placed India immediately south of Eurasia. Multiple workers have recently tackled this issue, with a detailed analysis by Huang et al. (2013) providing insight for inclination shallowing corrections that they suggest should be applied to previous studies in this region that show evidence for inclination shallowing. Studies such as Dupont-Nivet et al. (2010), Yi et al. (2011), and van Hinsbergen et al. (2012) seem to be converging upon an Eocene age of collision, ca. 50–55 Ma, which is the most frequently cited age interval for collision initiation across most of the length of the orogen.

Other notable lines of reasoning supporting Eocene collision initiation are an apparent decrease in the rate of northward motion of India (Klootwijk et al., 1992; Acton, 1999; Cande and Stegman, 2011), the timing of ultrahigh-pressure metamorphism of the leading Indian margin (Leech et al., 2005), cessation of marine facies and first arrival of Asian detritus on the Indian plate at ca. 50 Ma (e.g., Garzanti et al., 1987; Green et al., 2008), and Eocene continental molasse sedimentation (e.g., Clift et al., 2002).

In this paper, we will determine whether data in the Ladakh region can be interpreted to support Oligocene-aged collision, as stated by Aitchison et al. (2007). Specifically, the Upper Oligocene Basgo Formation of the Indus Basin, which lies directly atop the Eurasian plate, has been identified by Garzanti and Van Haver (1988) to be the base of the continentally derived Indus Group, with more traditional Indus molasse (the Choksti Formation) overlying the Basgo Formation (Aitchison et al., 2007). There are two major issues with this interpretation. First, the age of the Basgo Formation has since been revised from Maastrichtian (Garzanti and Van Haver, 1988) to Oligocene (Bajpai et al., 2004), but this revision was not accompanied by an update in the stratigraphic location of the Basgo Formation with respect to the remainder of the Indus Basin. Second, while input from the Ladakh batholith is clear from cobbles and boulders of the underlying granites (Garzanti and Van Haver, 1988), derivation of detritus from the Indian plate has not been demonstrated, rendering this unit as suspect regarding its relevance to the debate about the timing of collision initiation.

We first discuss the location of the Basgo Formation within the overall stratigraphy of the Indus Basin. Then, we present detrital zircon U-Pb dates that show that Basgo sandstone beds were sourced from the Indian plate, thereby demonstrating mixed provenance. However, based on detrital zircon (U-Th)/He thermochronology (ZHe), it appears that the source region for these zircons experienced early Cenozoic exhumation well before deposition. Collectively, these data can be interpreted to suggest that India-Eurasia collision drove the emergence of the precollisional Indian passive margin by early Eocene time. There is no evidence from the Basgo Formation that collision initiated during the Oligocene, counter to the claim of Aitchison et al. (2007).

CENOZOIC INTERMONTANE BASINS OF THE INDUS-TSANGPO SUTURE ZONE

The Indus-Tsangpo suture zone extends along the Yarlung River to the east and the Indus River to the west and consists of ophiolitic material, forearc basin deposits, and intermontane basin clastic strata. The intermontane basins along the Yarlung River are relatively isolated from one another (Fig. 1A), but they have been correlated across several hundred

Figure 1. (A) GTOPO30 shaded relief map overlain by Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model, with Cretaceous–Miocene intermontane basins shown in black (from Searle, 1986; Yin et al., 1999; Aitchison et al., 2002). (B) Geologic map of Indus-Tsangpo suture zone to the west of Leh. All faults are part of the main Zanskar back thrust system (Searle et al., 1990). Star in NW corner shows location of exposed fault contact between the Basgo Formation and the Ladakh batholith. This location is along the Sham trekking route between the villages of Yangthang and Hemis Shupachan. (C) Geologic map of area around Likir showing sample locations and detrital zircon (U-Th)/He thermochronology (ZHe) age ranges. Filled circles depict geographic locations, whereas filled squares depict samples from this study. The geologic units in the explanation comprise two sections—the Zanskar Gorge and Basgo sections. The units are listed in depositional order (after Garzanti and Van Haver, 1988; Clift et al., 2002). TSS—Tibetan sedimentary sequence.
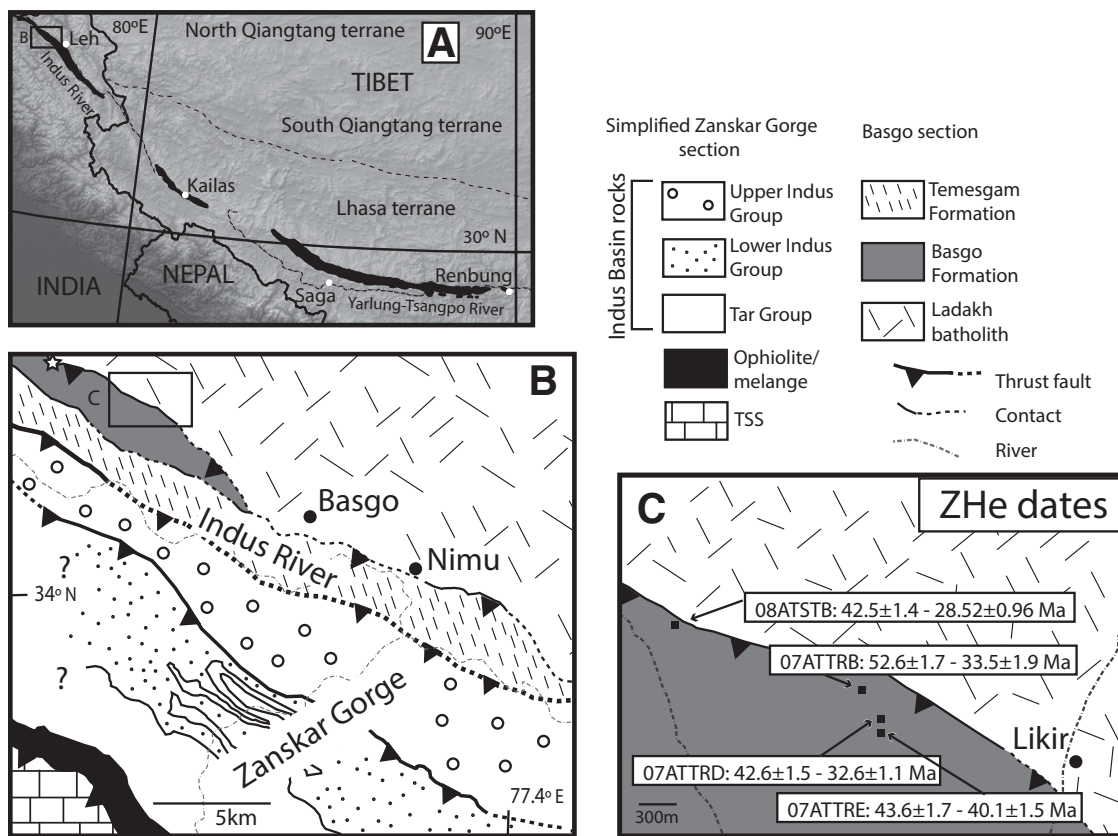
kilometers (Aitchison et al., 2002). However, because most of these basins contain an abundance of coarse clastic fill with few fossils or volcanogenic layers in all but the youngest strata (e.g., DeCelles et al., 2011), the ages of many important units are not well known, rendering these correlations suspect. Further complicating the usage of these basins as markers for the question of collision initiation is the difficulty of demonstrating mixed provenance, which is key to the argument that any particular unit unequivocally records this event.

The most thoroughly studied of the Indus-Tsangpo suture zone depocenters lies along the Indus River valley in the Ladakh region of NW India and is referred to as the Indus Basin (e.g., Garzanti and Van Haver, 1988; Henderson et al., 2010). An important cross section through the traditional Indus Basin stratigraphy is spectacularly exposed in the Zanskar Gorge (34°07′N, 77°13′E), and although our study area is outside this region, a brief discussion of its stratigraphy is merited for the sake of context and comparison.

Understanding of the traditional stratigraphy in the Zanskar Gorge is hampered by difficulty in accessing key contacts and complex structural geology that repeats relatively monotonic units. Nevertheless, multiple workers have attempted to map and understand the evolution of this type locality, with varied results (see synopsis in Henderson et al., 2010). In Figure 2, the differences in the stratigraphy of Clift et al. (2002) and Henderson et al. (2010) highlight some of this complexity. For example, Clift et al. (2002) followed the original definition of the Tar Group (Garzanti and Van Haver, 1988) as marine sediments only, whereas Henderson redefined it and included nonmarine sediments. Because the Basgo section is separate from the Zanskar Gorge section, we are able to significantly simplify the Indus Basin stratigraphy for our purposes, as our data do not bear on that debate.

In the simplified version of the stratigraphy, the Lower Indus Group, with middle Eocene maximum depositional ages, conformably overlies the uppermost marine strata and is separated from the Upper Indus Group by a fault. The Upper Indus Group has maximum depositional ages that may be as young as Miocene (Henderson et al., 2010). The uppermost marine limestones of the Indus Basin are 54.9–49.4 Ma (Henderson et al., 2010), and the cessation of marine deposition is interpreted to reflect closure of the Indus Basin during Ypresian (late early Eocene) collision.

The work presented here focuses on the Indus Basin units that outcrop to the west of the Zanskar Gorge. The Basgo Formation, where we have observed it, consists of alluvial conglomerates or braid-plain sandstones (Garzanti and Van Haver, 1988), and it is faulted atop the Cretaceous-Paleogene Ladakh batholith. In Figure 3, the Basgo Formation, which must have been originally deposited horizontally, is clearly dipping to the south, implying that it has been thrust to the north atop the Ladakh batholith. Furthermore, along a local trekking route, just before descending into the village of Hemis Shupachan, the contact is exposed, and fault gouge is present (star in Fig. 1B). The "Basgo section," which includes the conformably overlying prograding deltaic sediments of the Temesgam Formation (Garzanti and Van Haver, 1988), is separated from the Upper Indus Group by another fault (Fig. 1B).

This study		Clift et al. 2002	Henderson et al. 2010	
Zanskar Gorge	*Basgo*			
Upper Indus Group	Temesgam	Nimu	Upper Nimu	
	Basgo →		Lower Nimu	
	Ladakh batholith	Choksti Conglomerate	Choksti Formation	
Lower Indus Group		Nurla	Nurla	
		Nummulitic Limestone	Nummulitic Limestone	Tar Group
		Chogdo	Chogdo	
Tar Group		Jurutze	Sumda	
			Jurutze	

Figure 2. Simplified stratigraphy used in this work, which follows Clift et al. (2002). We include the stratigraphy of Clift et al. (2002) and Henderson et al. (2010) to highlight the difficulty in understanding Indus Basin stratigraphy, and to show where the unit in question, the Basgo Formation, may fit into the overall framework. In our simplified stratigraphy, we identify the major back thrusts that separate the major units.

Figure 3. Photograph of the contact between the Basgo Formation to the south and the Ladakh batholith to the north. The contact is dashed because it is not exposed. Note the south-dipping strata of the Basgo Formation, implying that it has been thrust to the north atop the batholith. Photo taken looking west. Line of ~25 trekkers for scale.

As such, there is no evidence that traditional Indus Basin molasse stratigraphically overlies the Basgo or Temesgam Formations. Rather, both the Lower and Upper Indus Groups, the latter of which includes the Choksti Formation mentioned by Aitchison et al. (2007), are stratigraphically below the paleontologically dated Upper Oligocene Basgo Formation (Bajpai et al., 2004) and have been back thrusted to the north (Searle et al., 1990). Thus, based upon the structure and age constraints, the Basgo Formation not the stratigraphic base of the Indus Basin (Fig. 2).

In order to further understand the Basgo Formation, we first used U-Pb detrital zircon geochronology to evaluate its provenance. A wealth of such data exists for the Indus Basin strata exposed in the Zanskar Gorge (Fig. 4A; Wu et al., 2007; Henderson et al., 2010). This provides a simple means by which to compare the Basgo Formation provenance with the provenance of other Indus Basin units. Additionally, ZHe dates record cooling through the nominal bulk closure temperature of 180 °C (Reiners et al., 2004) and could provide information about both the maximum age of deposition of the Basgo Formation and the exhumation of the source region.

ESTABLISHING PROVENANCE OF THE BASGO FORMATION

U-Pb Methods

Sandstone samples of the Basgo Formation were collected from several locations in and around a paleontological sampling locality of Bajpai et al. (2004), and they are listed in terms of relative stratigraphic height. Lowest is sample 08ATSTB, collected from a distinctive yellow outcrop proximal to the contact with the Ladakh batholith. Next, 1.6 km to the east, sample 07ATTRB was collected from the most ostracod-rich section of Bajpai et al. (2004; their location TR2). Sample 07ATTRB is stratigraphically equivalent to sample 07ATTRD, which was collected 0.3 km to the southeast. The final sample, 07ATTRE, is proximal to and stratigraphically above sample 07ATTRD.

The samples were crushed and sieved, and zircon grains were separated using standard magnetic and gravimetric techniques. U-Pb detrital zircon dates for samples 07ATTRD and 07ATTRE were obtained using laser-ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the University of Arizona Laserchron facility, with procedures detailed in Gehrels et al. (2008),
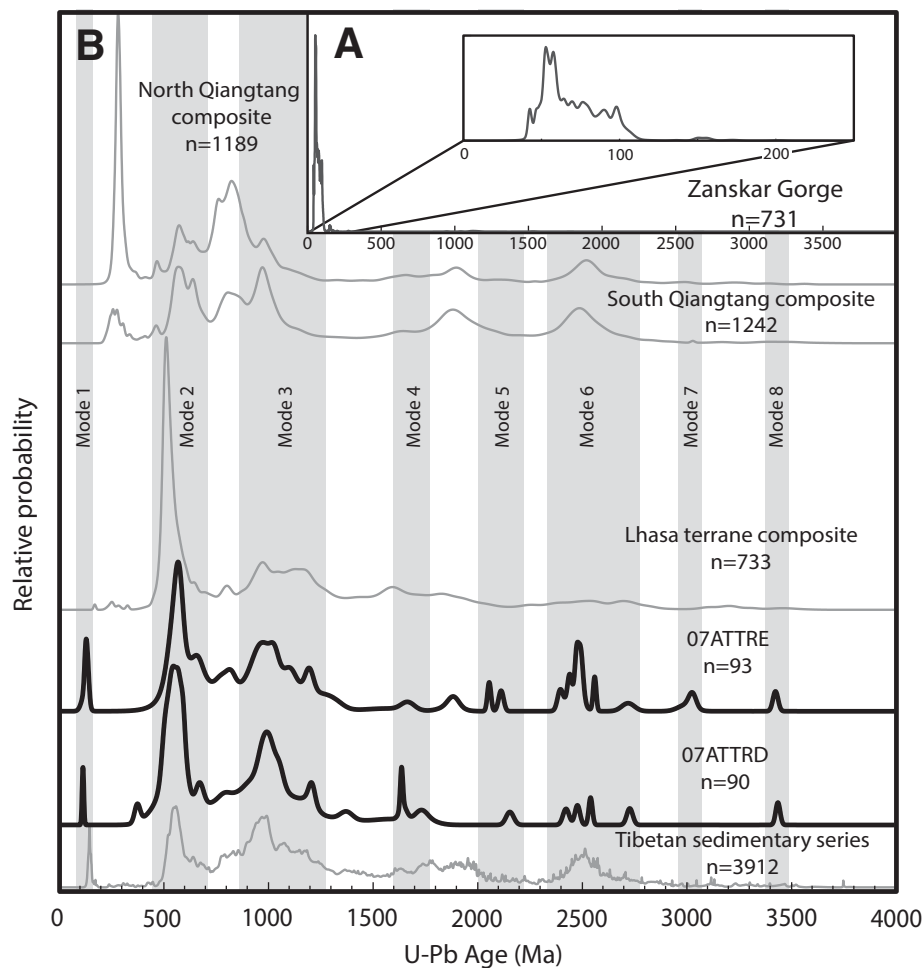
Figure 4. (A) Compilation of detrital U-Pb data from classic Indus Group section in the Zanskar Gorge (Wu et al., 2007; Henderson et al., 2010). Curve is plotted at a different scale than those in B, but x axis is the same. (B) Stacked probability density curves, from bottom to top, of Indian detrital U-Pb data (Gehrels et al., 2011), Basgo samples 07ATTRD and 07ATTRE from this study, and Eurasian U-Pb data (Gehrels et al., 2011). Gray bands signify important modes.

and those specific to our analytical session in the Data Repository.[1]

U-Pb Results

Detrital zircon U-Pb dates from both Basgo samples ($n = 90$ for sample 07ATTRD and $n = 93$ for sample 07ATTRE) are similar, displaying dates ranging from ca. 3400 Ma to 90 Ma, indicating that, at the 95% confidence interval, no Cenozoic zircons compose any subpopulation that is greater than ~6% of the total population (Vermeesch, 2004). Probability density curves from both samples were calculated and plotted using in-house software at Arizona State University (Fig. 4B; Data Repository [see footnote 1]).

Potential Source Regions

For a northern, Eurasian source, possibilities include the Transhimalayan arcs (Kohistan-Ladakh-Gangdese), the Lhasa terrane, and the Qiangtang terrane. Wu et al. (2007) and Henderson et al. (2010) examined the classic Indus Group section, in the nearby Zanskar Gorge, and interpreted that the detrital zircon U-Pb signature is predominantly that of the Late Cretaceous to Cenozoic Transhimalayan Ladakh batholith (Fig. 4A). However, because we found no Cenozoic grains, a better comparison is that of Gehrels et al. (2011). These authors published a compilation of pre-Cenozoic detrital zircon U-Pb dates from various terranes, including the Lhasa terrane, and both the South and

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[1]GSA Data Repository Item 2013314, detailed U-Pb methods, and full U-Pb and (U-Th)/He data tables, is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

North Qiangtang terrane (Fig. 4B). These terranes share similarities in their age spectra and are interpreted as rifted Gondwanan terranes.

For a southern, Indian source, Gehrels et al. (2011) demonstrated that the Indian passive margin sequence, the Tibetan sedimentary series, also contains a Gondwanan detrital zircon signature. In detail, the northern and southern potential source regions' age spectra differ based upon the presence or absence of Mesozoic, Paleozoic, and Archean modes, as well as the relative abundances of the Neoproterozoic and Mesoproterozoic modes (Fig. 4B).
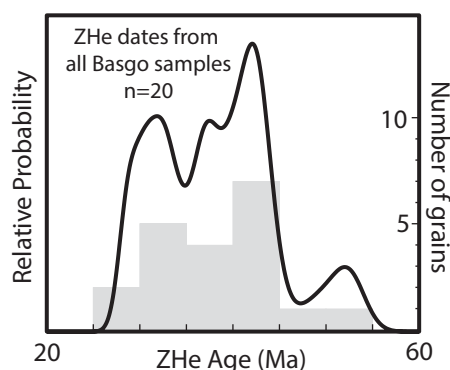
Interpretation

There are eight major modes that we have highlighted in Figure 4B, all of which match data in the Tibetan sedimentary series compilation curve, with modes 1, 7, and 8 absent in all potential Eurasian-source age spectra. Importantly, all major Tibetan sedimentary series modes are present in the Basgo sandstone age spectra. Furthermore, the Zanskar Gorge spectrum contrasts strongly with those of the Basgo Formation due to the apparent absence of a Cenozoic population in our samples. It is extremely difficult to envision a scenario in which the North and South Qiangtang and Lhasa terranes contributed to the Basgo sandstones without the incorporation of even a single Cenozoic Transhimalayan grain. Thus, a strictly Eurasian source area is highly unlikely. Furthermore, a mixed Indian-Eurasian provenance hypothesis would require some extraordinarily complex paleogeography in order to exclude proximal, Cenozoic Eurasian grains of the Transhimalayan batholiths. Therefore, we conclude that the simplest explanation is most likely—that the vast majority of zircons in the Basgo sandstones were derived from the Indian Tibetan sedimentary series. Coupled with the boulders and cobbles from conglomeratic layers that are clearly derived from the Ladakh batholith, the Basgo Formation thus contains evidence for mixed provenance.

EXHUMATION OF THE ZIRCON SOURCE REGION

ZHe Methods

ZHe dates from all samples were obtained in the Noble Gas, Geochronology and Geochemistry Laboratory at Arizona State University using conventional techniques, detailed in van Soest et al. (2011). Age ranges are plotted in Figure 1C, and a probability density curve for all ZHe data ($n = 20$) is plotted in Figure 5. Analytical results are listed in the Data Repository (see footnote 1).

Figure 5. Probability density curve and histogram of all detrital zircon (U-Th)/He thermochronology (ZHe) data from this study.

ZHe Results and Interpretation

The ZHe dates range from 52.6 ± 1.7 Ma to 28.52 ± 0.96 Ma (2σ) and provide information about the low-temperature history of the source area(s). Based on the detrital zircon U-Pb results described herein, we infer that the majority of these grains were derived from Tibetan sedimentary series rocks that were exposed and eroding prior to or during late Oligocene Basgo deposition. This inference is further supported by the stark difference in published ZHe dates from the Ladakh batholith, wherein all dates are Oligocene and younger (<30.9 ± 5.8 Ma; Kirstein et al., 2009). Notably, 70% of the zircons yield (U-Th)/He cooling dates of Eocene age. There are two possible explanations. First, these dates may be due to burial and heating within the Tibetan sedimentary series, which was certainly thick enough, in places, to reach >180 °C, the nominal ZHe closure temperature (Liu and Einsele, 1994; Reiners et al., 2004; geothermal gradient of 25 °C/km). Second, these dates could be explained by partial resetting due to postdepositional reheating of the Basgo Formation. We prefer the first explanation because this section of the Indus Group contains relatively unaltered sandstones when compared to the reheated Zanskar Gorge section, and they are often poorly cemented in thin section and friable in hand sample. However, even if the latter explanation is the case, the initial ages prior to reheating must have been older than the measured age. Thus, these are minimum exhumation dates for the source region.

IMPLICATIONS

Clasts within more conglomeratic units (Garzanti and Van Haver, 1988; Bajpai et al., 2004) indicate that the Basgo Formation contains sediments from Eurasia, whereas the detrital zircon U-Pb data from Basgo sandstones strongly suggest that the major source for sand-sized Basgo detritus was India, specifically, the Tibetan sedimentary series. While it is possible that the mixed India-Eurasia provenance of the Basgo Formation can be interpreted as evidence for deposition immediately after collision commenced, it is unlikely to be the oldest unit within the Indus Basin that demonstrates mixed provenance. Furthermore, based on the ZHe data set, the provenance region did not experience a single phase of rapid and uniform erosion through the ~180 °C isotherm in late Oligocene time, although these data do not rule out a rapid phase of erosion from much more shallow levels since that time. The simplest explanation implies that exhumation and cooling of much of the source region were related to an older deformational event. The majority of the Basgo ZHe cooling ages are Eocene, corresponding to the time ascribed by many researchers to the onset of India-Eurasia collision. We interpret that the Tibetan sedimentary series in this region had been incorporated into the Himalayan-Tibetan orogenic system by Eocene time at the minimum, and was eroding as a consequence.

This scenario requires an interesting paleogeography, and it could point to the existence of a longitudinal paleo–Indus River as the source of the sandstones, while more local processes from a transverse system governed the deposition of the conglomerates. This is, in fact, supported by the Basgo facies described by Garzanti and Van Haver (1988), which include both alluvial-fan conglomerates and braid-plain sandstones. A longitudinal river would imply that such an axial system was already established by Oligocene time, further supporting the idea of collision prior to this time (Clift et al., 2001). However, this scenario requires that such a paleo–Indus River almost exclusively sampled the Indian margin while almost completely ignoring the Transhimalayan arc.

Our data are collectively consistent with the large body of evidence that favors India-Eurasia collision at ca. 55–50 Ma or earlier in the western Himalayan-Tibetan orogenic system (e.g., Rowley, 1996; Green et al., 2008). While others have suggested, correctly, that such evidence could be explained by collision between the Transhimalayan island arc and the Indian margin (e.g., Khan et al., 2009), there is no evidence of an Oligocene-aged collision zone in the northwestern Indian Ladakh Himalaya (e.g., Treloar et al., 1989). Thus, the burden of proof remains for proponents of Oligocene-aged collision to convincingly demonstrate that the terminal India-Eurasia collision occurred on a different suture zone during Oligocene time at this sector of the orogen. However, our data do permit

a recent hypothesis put forth by van Hinsbergen et al. (2012), wherein at ca. 50 Ma, an extended microcontinental fragment of India that contained rocks of the Tibetan sedimentary series collided with Asia, and this was followed by collision of cratonic India, or "hard collision," at ca. 25 Ma. Regardless, understanding whether the timing of collision along the length of the Indus-Tsangpo suture zone is variable will require further studies of the kind described here, wherein multiple methods are utilized in other Cenozoic intermontane basins along the suture zone.

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