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Where does India end and Eurasia begin?

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[1] The Indus Suture Zone is defined as the plate boundary between India and Eurasia. Here we document geochronological data that suggest that Indian rocks outcrop to the north of this suture zone. The inherited age spectrum of zircons from mylonitic gneiss collected in the southern part of the Karakorum Batholith is similar to those obtained from the Himalayan Terrane, the Pamir and is apparently Gondwanan in its affinity. These data are taken to indicate that the Karakorum Terrane was once a component of Gondwana, or at least derived from the erosion of Gondwanan material. Several continental ribbons (including the Karakorum Terrane) were rifted from the northern margin of Gondwana and accreted to Eurasia prior to India-Eurasia collision. Many therefore consider the Karakorum Terrane is the southern margin of Eurasia. However, we do not know if rifting led to the creation of a new microplate(s) or simply attenuated crust between Gondwana and these continental ribbons. Thus there is a problem using inherited and detrital age data to distinguish what is "Indian" and what is "Eurasian" crust. These findings have implications for other detrital/inherited zircon studies where these data are used to draw inferences about the tectonic history of various terranes around the world.

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1. Introduction

[2] The Himalayan Terrane is often subdivided into three litho-tectonic units that stretch along the length of the mountain range [*Yin*, 2006]. These units are referred to as the Lesser Himalayan Sequence (LHS), Greater Himalayan Sequence (GHS) and the Tethyan Himalayan Sequence (THS) [*Yin*, 2006] (Figure 1). U/Pb isotopic dating of detrital zircon populations has proven a useful tool for distinguishing the similarities and differences between

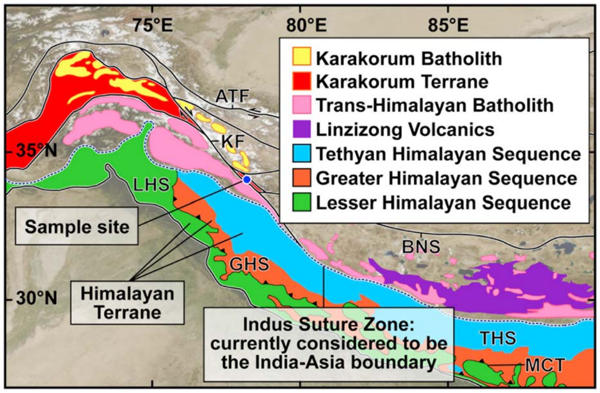

Figure 1. This map shows the location of the samples that were analyzed in this study, as well as the location of the various geological "units" (Lesser Himalayan Sequence (LHS), Greater Himalayan Sequence (GHS), Tethyan Himalayan Sequence (GHS), Linzizong Volcanics, Trans-Himalayan Batholith and Karakorum Batholith) and traces of major structures (Altyn-Tagh Fault (ATF), Bangong Nujiang Suture Zone (BS), Karakorum Fault (KF), the Indus Suture Zone (ISZ)) and the Main Central Thrust (MCT). The ISZ is currently considered the tectonic boundary between India and Eurasia [*Thakur and Misra*, 1984]. The geology map was modified from *Yin* [2006] and *Phillips* [2008].

these sequences [*Myrow et al.*, 2003; *DeCelles et al.*, 2004]. Such data have been used to infer that the Lesser, Greater and Tethyan Himalayan sequences represent proximal to distal facies of a passive continental margin that developed on the northern margin of the Indian plate [*Myrow et al.*, 2003]. This work also highlighted that the Main Central Thrust (MCT) could not be a fundamental crustal boundary that separated the Indian craton and an allocthonous accreted terrane [*Myrow et al.*, 2003] (Figure 1). This supports the work of *Ahmad et al.* [2000] who state that the MCT represents the boundary between the low grade and older (early mid Proterozoic) Lesser Himalayan Sequence and the higher grade and younger (late Proterozoic) Greater Himalayan Sequence [*Parrish and Hodges*, 1996]. Instead, the Indus Suture Zone is considered to be the major crustal boundary between the Indian plate and Eurasia [*Thakur and Misra*, 1984].

[3] We dated zircons from a gneiss and a crosscutting leucogranite dyke from the Karakorum Terrane (north of the Indus Suture Zone and the Himalayan Terrane) to determine their provenance. The samples were collected in a gorge between the villages of Shyok and Durbuk in NW India, where networks of leucogranite dykes crosscut mylonitic gneiss. According to the most detailed geological map of the region and ID-TIMS dating, these units are considered to be ~82 Ma Tangste orthogneiss and are crosscut by <15 Ma Tangste-Darbuk leucogranites [*Phillips*, 2008].

2. Sample Description

[4] The gneiss (LAD08–04) is primarily composed of quartz, biotite, plagioclase and hornblende and is best described as quartz-biotite gneiss. The sample also contains accessory minerals including epidote, magnetite, titanite and zircon. Most quartz grains exhibit undulose extinction and some grains show evidence of grain boundary migration and subgrain development. The sample exhibits S/C and C′ fabrics delineated by biotite and hornblende overgrowths.

[5] The crosscutting leucogranite dyke sample (LAD08–03) is primarily composed of quartz, plagioclase, microcline and orthoclase, with minor biotite/chlorite and garnet xenocrysts. This sample contains allanite, titanite and zircon as accessory minerals. Myrmekitic textures are observed at the grain boundaries between quartz and feldspars. The dyke has also been deformed, as quartz and feldspar grains exhibit undulose extinction. Some quartz and feldspar megacrysts are also fragmented due to deformation, while other quartz crystals have been recrystallized.

3. Shrimp Methodology

[6] Approximately 2 kg of each sample was crushed, milled and subject to standard mineral separation techniques for zircon. These zircons were hand picked and set in epoxy resin in standard sized (~2 cm) SHRIMP mounts with a sufficient number of Temora-2 zircon standards [*Black et al.*, 2004]. The mounts were then polished to expose the midsection of each zircon grain. The polished zircons were examined with an optical microscope and photographed under transmitted and reflected light. Cathodoluminescence (CL) images of the zircons were obtained with a Hitachi FESEM.

[7] The cores and rims of multiple zircon grains from each sample were analyzed with SHRIMP-RG at the Research School of Earth Sciences, The Australian National University. These were analyzed over the course of five SHRIMP sessions. The Temora-2 zircon standard was used as the U/Pb standard (417 Ma [*Black et al.*, 2004]), with a standard analyzed for every three unknown zircon analyses. Uranium concentrations [U] were normalized to SL13 (U = 238 ppm). Data from each session were

Table 1. Age and Chemistry of the Zircon Cores and Rims of the Samples That Were Analyzed in This Study

	Quartz-Biotite Gneiss		Leucogranite Dyke
	Zircon Core	Zircon Rim	Zircon Core
Age	109–2700 Ma	13–290 Ma	17.0–19.6 Ma
Uranium (ppm)	25–5154	150–641	1990–14,500
Thorium (ppm)	26–2400	2–357	95–1830
Th/U	0.09–3.45	0.01–0.58	0.04–0.13
^{204}Pb	<2.16	<1.50	<0.66
$^{207}Pb/^{206}Pb$	0.04–0.25	0.05–0.06	0.04–0.09

reduced using SQUID 2 (http://sourceforge.net/projects/squid2/files/). Common lead in zircons was corrected by using a Stacey-Kramer's common Pb composition for the inferred magmatic age. Count rates were normalized to the secondary-beam-monitor to correct for total beam fluctuations. All ages younger than 900 Ma are reported using the ^{207}Pb corrected $^{206}Pb/^{238}U$ system due to the errors associated with low yields of ^{204}Pb, ^{207}Pb and ^{208}Pb from zircons of this age. This method effectively assumes each analysis is a mixture of radiogenic and common lead, and this is unmixed from the measured $^{207}Pb/^{206}Pb$ ratio. All ages older than 900 Ma are reported using the ^{204}Pb corrected $^{207}Pb/^{206}Pb$ ratio.

4. Geochronology Results

[8] Many zircon cores (n = 106) and several zircon rims (n = 5) of the gneiss were analyzed (see Data Set S1 in the auxiliary material).[1] The range of uranium and thorium concentrations as well as Th/U, ^{204}Pb and $^{207}Pb/^{206}Pb$ measurements from zircon cores and rims are summarized in Table 1. The age of the cores range between 109 and 2700 Ma and age peaks are observed between 450 and 600 Ma, ~700 and 850 Ma, 1000 and 1200 Ma, and at ~1500 Ma. The age of the rims range between 13 and 290 Ma, where each rim analysis was younger than its corresponding core.

[9] Forty-seven zircon grains from the leucogranite dyke were analyzed (see Data Set S1). The range of uranium and thorium concentrations as well as Th/U, ^{204}Pb and $^{207}Pb/^{206}Pb$ measurements from zircon grains are summarized in Table 1. One analysis yielded much higher counts of ^{204}Pb [84.63 c/s] and a nonradiogenic $^{207}Pb/^{206}Pb$ ratio [0.673] and was therefore omitted from further interpretation as it may have gained or lost Pb and/or U. The age of the leucogranite zircon grains range between 17.0 and 19.6 Ma. These yield a weighted mean age of 18.1 ± 0.1 Ma [0.76%], MSWD = 5.3, 2σ, (n = 46). However, there is a positive correlation between [U] and apparent age for [U] > ~6000 ppm. This correlation is due to a matrix-dependent sputtering effect associated with the ablation of metamict (or partially metamict) zircon [*White and Ireland*, 2011]. We therefore suspect that the ages obtained from zircons with [U] > ~6000 ppm in this sample are compromised by a matrix effect, and these ages are not geologically significant. We therefore excluded the results with [U] > 6000 ppm and recalculated a weighted mean age from the remaining SHRIMP analyses [17.9 Ma ± 0.1 Ma [0.6%], MSWD = 2.1, 2σ, (n = 33)]. The lower MSWD obtained from this calculation indicates that the weighted mean is more representative of a single age of formation.

5. Discussion

[10] The SHRIMP results show that the zircon cores from the Karakorum quartz-biotite gneiss produce scattered peaks between 109 Ma and 2250 Ma. Since we did not observe symplectic textures or leucosomes, the lack of one dominant age and lack of evidence of melting implies that this sample is probably a deformed and metamorphosed sedimentary rock, and not a quartz-rich diorite melt. The youngest age obtained from the gneiss is 109 Ma, and this serves to constrain the maximum age of the sediment.

[11] A minimum age of 17.9 Ma ± 0.1 Ma is provided by the SHRIMP analyses of zircons from the crosscutting 17.9 Ma leucogranite dyke. We did not obtain any evidence of older inherited zircon cores in the leucogranite. We therefore only use the magmatic age of this sample to constrain to the minimum depositional age of the protolith of the quartz-biotite gneiss sample.

[12] The geochronology results indicate that the quartz-biotite gneiss is a different geological unit than the ~82 Ma Tangste orthogneiss [*Phillips*, 2008]. In addition it is evident that the ~18 Ma crosscutting leucogranite sample represents a different phase of magmatism than the < 15 Ma Tangste-Darbuk leucogranites shown on the geological map of *Phillips* [2008]. However, the age that was obtained from the leucogranite dykes corresponds to the ~18 Ma U/Pb SHRIMP age obtained for the nearby Tangste Leucogranite dykes, and suggests that the two dyke samples probably relate to the same magmatic/partial melting event [*Searle et al.*, 1998].

[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/gc/2011gc003726.

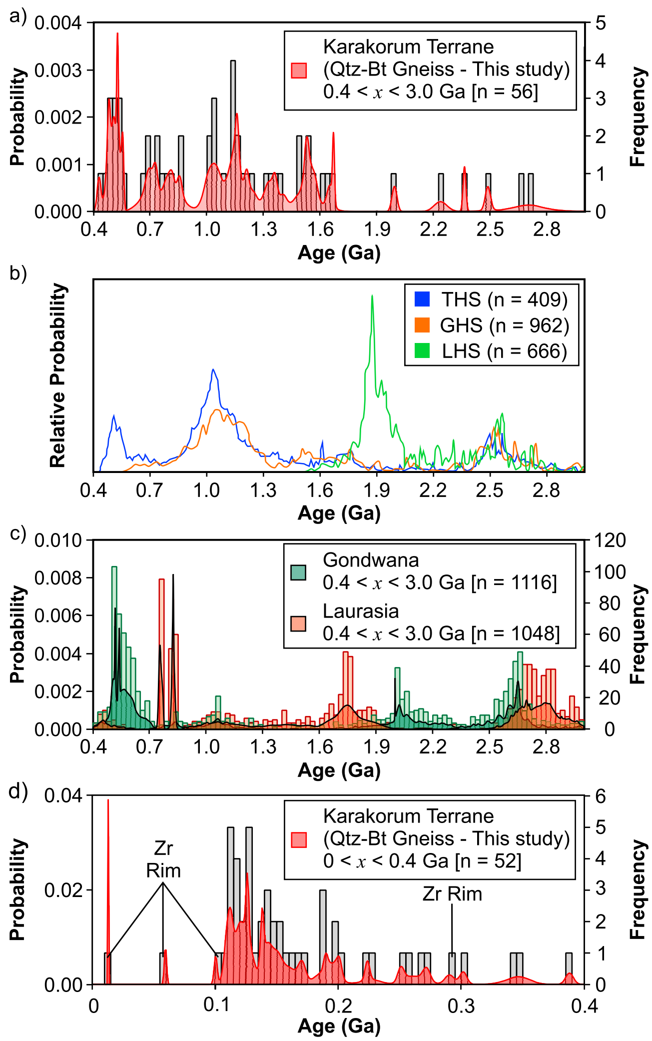

Figure 2. (a) The relative probability and frequency plots of the SHRIMP results of detrital/metamorphic zircons from the Karakorum gneiss sample that were analyzed during this study are similar to (b) the age spectra obtained from multiple samples of the Tethyan Himalayan Sequence (THS) and Greater Himalayan Sequence (GHS) [*DeCelles et al.*, 2004]. The Karakorum gneiss samples also do not yield the ~1900 Ma age peak obtained from the Lesser Himalayan Sequence (LHS) [*DeCelles et al.*, 2004]. (c) The age spectra derived from the Karakorum gneiss sample better reflect the dominant age peaks obtained from Gondwana, rather than Laurasia according to a recent compilation of the detrital age spectra of each supercontinent [*Lancaster et al.*, 2011]. (d) Inherited ages less than 0.4 Ga obtained from the Karakorum gneiss share some similarity with detrital age spectra obtained from the basement rocks of the Pamir and Qiantang Terrane [see *Ducea et al.*, 2003, Figure 3]. The relative probability and frequency plots in Figures 2a, 2c, and 2d were generated with the AgePlot [*Sircombe*, 2004]. The relative probability plot in Figure 2b was modified from *DeCelles et al.* [2004]. The colors that are used to plot each sequence correspond with those used in Figure 1.

[13] Interestingly, the inherited age spectra of the quartz-biotite gneiss are very similar to the 400–3000 Ma ages obtained from the Greater Himalayan Sequence and the Tethyan Himalayan Sequence [*Myrow et al.*, 2003; *DeCelles et al.*, 2004] (Figures 2a and 2b). The dominant 450–600 Ma age peak, the presence of 2000–2500 Ma ages and the lack of zircons between 1700 and 1900 Ma indicate that the Karakorum gneiss was probably derived from sediments that were shed from Gondwana or a Gondwanan fragment (Figure 2c). This is consistent with paleontological work that found Gondwanan, or mixed Gondwanan-Cathaysian fossil assemblages in the Karakorum Terrane [*Sharma et al.*, 1980; *Xingxue and Xiuyuan*, 1994; *Srivastava and Agnihotri*, 2010].

[14] The ~400–600 Ma age peak is also found in the basement rocks of the Pamir (north of the Karakorum Terrane) and the Qiangtang Terrane (east of the Karakorum Terrane) and this peak was interpreted to indicate a Gondwanan age signature [see *Ducea et al.*,

2003, Figure 3]. The relative proportion of ~100–400 Ma zircons in the Karakorum gneiss (Figure 2d) is greater than what was found for the LHS, GHS and THS [*DeCelles et al.*, 2004] and is less than was obtained from the basement rocks of the Qiangtang Terrane and the Pamir [see *Ducea et al.*, 2003, Figure 3].

[15] Many different tectonic/geological models could be proposed to explain the similarities between the age spectra each of the different terranes discussed above, however we recognize the problems associated with making such comparisons to construct a tectonic model. We therefore only take our data to confirm that the Karakorum Terrane was once a component of Gondwana, or was derived from the sediment that was shed off Gondwana or a Gondwanan fragment.

[16] It is generally accepted that various continental ribbons were torn from Gondwana and that these ribbons accreted to Eurasia before India [*Klootwijk et al.*, 1994; *Ali and Aitchison*, 2008]. Our geochronological data lend support to the idea that the Karakorum Terrane was derived from Gondwana or a rifted fragment of Gondwana. However, as many workers consider the Karakorum Terrane to represent the southern margin of Eurasia, we must consider when it (and other Gondwanan fragments) ceased being Gondwanan/Indian and became "Asian." Here lies a challenge, as we do not necessarily know (1) when the Karakorum Terrane and each of the other Gondwanan fragments were torn from the supercontinent, (2) if a new oceanic plate was created when the Karakorum Terrane was rifted from Gondwana, and/or (3) if crustal material was tectonically transferred from one plate to another. Another related challenge lies in understanding how the position of each rifted continental fragment changed in relation to India and Eurasia through time.

[17] Paleomagnetic data can be used to infer the latitude of some of these continental ribbons and their position relative to India [e.g., *Tan et al.*, 2010; *Lippert et al.*, 2011]. However, such data are limited to several locations across the orogen and these data are usually of relatively low accuracy in terms of constraining the paleolatitude of continental ribbons at discrete points in time. We can use the paleomagnetic data to infer that an oceanic plate must have existed between the two continental fragments if there was a great distance (i.e., >1000 km) between the continental ribbons in question at a particular time. However, we cannot prove that an additional plate existed between the two continental ribbons, as the continental ribbons may remain on the same plate and be separated by attenuated continental crust.

[18] Much work has been devoted to establishing when particular suture zones closed between India and Eurasia [e.g., *Rowley*, 1996; *Zhu et al.*, 2006; *Aitchison et al.*, 2007; *Baxter et al.*, 2009; *Henderson et al.*, 2011]. However, as we are unsure whether crustal extension led to the creation of new oceanic plates between India and the fragments that were torn off its northern margin, the closure of some of these suture zones may be incorrectly inferred, and so-called 'closure' merely reflects a time when the stress-field changed, deep marine rift basins were inverted and the crust thickened. Such processes would produce the same change in the sedimentary record that is currently attributed to the collision of India and Asia (i.e., a change from marine to continental sedimentation in the Indus Suture Zone [*Searle et al.*, 1987, 1988]). The timing of switches from deep marine sedimentation to continental sedimentation may reflect an episode of crustal shortening, rather than the cessation of subduction of large volumes of oceanic lithosphere and "the collision" of India and Eurasia.

6. Conclusions

[19] Inherited zircons from a mylonitic gneiss of the Karakorum Terrane, north of the currently accepted plate boundary between India and Asia, displayed an age similar to those found in the Tethyan Himalayan and Greater Himalayan sequences of the Indian plate, as well as those of the Pamir Terrane further to the north. We take this data to indicate that the Karakorum Terrane was once a component of Gondwana, or derived from sediments that were shed off the northern margin of Gondwana. Many workers consider that the particular rifted fragments of Gondwana mark the southern margin of Asia. However, there is a problem in defining when these Gondwanan continental ribbons cease being "Indian" and become "Asian." This demonstrates that care should be taken when using inherited and detrital zircon age spectra to infer information about the tectonic history of a region, and also in using these data as "fingerprints" of particular terranes/continents.

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