Geology

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Notes

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ABSTRACT

The timing and nature of the India-Asia collision, Earth's largest ongoing continent-continent collisional orogen, are unclear. Ultrahigh-pressure metamorphism of Indian continental margin rocks is used as a proxy for initial collision because it indicates subduction of India. Records of this metamorphism are preserved only at Kaghan Valley (Pakistan) and Tso Morari (Ladakh, India), separated by ~500 km and having published ages of peak pressure of 46.2 ± 0.7 Ma and 53–51 Ma, respectively. The apparent ~6 m.y. age difference may reflect multiple subduction events, a large promontory along the former Indian margin, or inadequate constraints on the time of peak pressure recrystallization at Tso Morari. We present 108 coupled, in situ U/Th-Pb and rare earth element (REE) analyses of zircons in two Tso Morari eclogites to obtain age and petrologic information. The ages range from ca. 53 Ma to 37 Ma, and peak at ca. 47–43 Ma. Flat heavy REE slopes and the absence of an Eu anomaly are compatible with eclogite-facies zircon (re)crystallization. This (re)crystallization probably occurred at ultrahigh pressure, because 64% of the analyses are from zircon included in ultrahigh-pressure garnet and omphacite. These results are consistent with those from Kaghan Valley, and suggest that a single, protracted ultrahigh-pressure metamorphic event occurred contemporaneously across much of the orogen, following initial contact of the Indian and Asian continents at ca. 51 Ma or later.

INTRODUCTION

The Himalaya represent the front of the India-Asia collision, and are dominantly composed of material scraped off the subducting Indian plate (Yin, 2006) (Fig. 1). Closure of the Tethys Ocean, which separated the two continents, involved accretion of multiple intra-oceanic arcs, and possibly microcontinents, before culminating in continent-continent collision (Mahéo et al., 2004; van Hinsbergen et al., 2011a). At least 12 phenomena have been proposed to indicate the initial collision of India and Asia (see reviews by Rowley, 1996; Yin and Harrison, 2000; Guillot et al., 2003; Najman, 2006; van Hinsbergen et al., 2011a): (1) cessation of marine sedimentation or change in sedimentary style; (2) mixing of Indian and Asian detritus; (3) sediment from one plate deposited on the other; (4) deposition of one sedimentary unit on both plates; (5) ultrahigh-pressure (UHP) metamorphism of Indian supracrustal rocks; (6) slowing of plate convergence; (7) reorganization of some or all of the global plate circuit; (8) equivalence of paleolatitudes of northernmost pre-collisional India with southernmost pre-collisional Tibet; (9) transfer of fauna from one plate to the other; (10) emplacement of mélange; (11) change of characteristics in upper plate magmatism; and (12) shortening of the northern Indian margin. Dating these phenomena has yielded interpreted collision ages ranging from 70 Ma to 35 Ma; most workers favor ages of ca. 55–50 Ma. An outstanding question regarding the initiation of collision is how its timing varied along strike. Constraints on the timing of UHP metamorphism suggest that subduction of Indian crust began ~6 m.y. later in the northwest than it did in the southeast (dates of ca. 46 Ma at Kaghan Valley versus ca. 53–51 Ma at Tso Morari; Kaneko et al., 2003; Leech et al., 2005; St-Onge et al., 2013). However, dates from Tso Morari have little petrogenetic information to support their connection to eclogite-facies metamorphism (O'Brien, 2006). In order to better constrain the timing of UHP metamorphism at Tso Morari, we present coupled U/Th-Pb and rare earth element (REE) data from 108 analyses of 103 zircons in two eclogites.

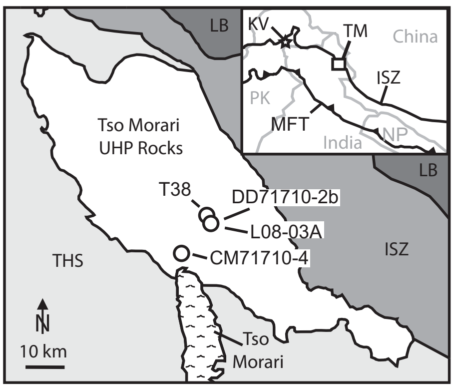

Figure 1. Sample location map, Tso Morari, India. Inset shows ultrahigh-pressure (UHP) locations in the Himalaya. ISZ—Indus-Yarlung suture separating Indian and Asian rocks; KV—Kaghan Valley; TM—Tso Morari; PK—Pakistan; NP—Nepal; MFT—Main Frontal thrust; LB—Ladakh Batholith; THS—Tethyan Himalayan Sequence. Sample T38 is a quartzofeldspathic gneiss dated by Leech et al. (2005); sample L08–03A is a mafic eclogite sample analyzed by St-Onge et al. (2013); samples CM71710–4 and DD71710–2b are eclogites analyzed in this study. GPS coordinates for DD71710–2B and CM71710–4 are 33°08.959′N, 078°21.439′E and 33°07.230′N, 078°17.090′E, respectively. Map modified from Epard and Steck (2008).

GEOLOGIC SETTING AND PETROLOGY

UHP rocks occur in two locations south of the Indus suture zone, which separates Indian and Asian rocks: in the Kaghan Valley of northern Pakistan, and north of Tso (Lake) Morari in northwestern India (Fig. 1). Ultrahigh pressures are confirmed by preserved coesite (O'Brien et al., 2001; Sachan et al., 2004). UHP rocks crop out within dominantly felsic Indian supracrustal rocks (e.g., de Sigoyer et al., 2004; Wilke et al., 2010a). Pressure-temperature (*P-T*) histories of the two UHP terranes are remarkably similar (e.g., Wilke et al., 2010a): (1) UHP conditions of ~2.7–3.6 GPa, 640–760 °C, (2) cooling during initial decompression to ~0.9–1.7 GPa, 500–640 °C, and (3) reheating at ~0.8–1.2 GPa, 650–720 °C. However, the timing of UHP metamorphism at the two sites may differ.

Two scenarios have been advanced: UHP metamorphism at 47–46 Ma at both localities (e.g., Kaneko et al., 2003; O'Brien, 2006; Wilke et al., 2010b), or at 47–46 Ma at Kaghan Valley and 53–51 Ma at Tso Morari (e.g., Leech et al., 2005, 2007; Guillot et al., 2007; St-Onge et al., 2013). The Kaghan Valley UHP event is well constrained at 46.2 ± 0.7 Ma (2σ) by U-Pb dating of zircon rims containing coesite inclusions (Kaneko et al., 2003). This is supported by a high-resolution–secondary ion mass spectrometry date of 44.9 ± 1.2 Ma from 35 eclogite zircons, a thermal ionization mass spectrometry date of 46.4 ± 0.1 Ma from an eclogite zircon, a multi-point allanite Th-Pb isochron of 46.4 ± 0.9 Ma, and $^{40}Ar/^{39}Ar$ phengite plateau dates of 47.3 ± 0.3 Ma and 47.5 ± 0.5 Ma and (Parrish et al., 2006; Wilke et al., 2010b; Rehman et al., 2013). Despite multiple efforts, similarly straightforward dates have not been obtained for Tso Morari UHP rocks. Sm-Nd garnet-glaucophane–whole rock, Lu-Hf garnet–omphacite–whole rock, and U-Pb allanite dating all yielded 55 Ma dates for interpreted UHP mineral growth, but with large uncertainties of 7–17 m.y. (de Sigoyer et al., 2000). Analyses (15) of metamorphic zircon rims from a quartzofeldspathic gneiss yielded a range of dates with clusters at 53.3 ± 0.7 Ma (3 analyses), 50.0 ± 0.6 Ma (5 analyses), and 47.5 ± 0.5 Ma (7 analyses)

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(Leech et al., 2005, 2007); but interpretation of these dates is controversial (c.f. O'Brien, 2006; see Fig. DR1 in the GSA Data Repository[1]). Recent data from St-Onge et al. (2013; analyses of metamorphic zircons in eclogitic prograde garnet cores and eclogite matrix yielded ages of 58.0 ± 1.4 Ma [2 analyses] and 50.8 ± 1.4 Ma [4 analyses], respectively) present similar difficulties (see Fig. DR1).

The apparent difference in the time of UHP metamorphism between Kaghan Valley and Tso Morari may indicate diachronous collision of an irregular Indian margin with a >500 km promontory (Guillot et al., 2007) or separate accretion events (Lister et al., 2001; White and Lister, 2012), of which only the younger may represent collision. Alternatively, the existing geochronology permits that the Kaghan and Tso Morari UHP metamorphism both occurred at ca. 47 Ma (Kaneko et al., 2003; O'Brien, 2006) and might together signal continent-continent collision.

PETROCHRONOLOGY

To address the uncertainty in UHP timing, U/Th-Pb and REE zircon data were acquired via laser ablation–split-stream inductively coupled plasma–mass spectrometry (for analytical methods see the Data Repository). This approach enables analysis of U/Th-Pb ratios and REE abundances from the same volume of material. In situ analyses were obtained from thin sections of samples CM71710–4 and DD71710–2b, collected ~10 km apart in the Tso Morari UHP terrane (Fig. 1). Both samples consist of garnet, omphacite, phengite, rutile, quartz, zoisite, amphibole, and sodic augite–plagioclase symplectite, with trace phases of zircon, pyrite, and titanite after rutile (Fig. DR2). Inclusion-rich idioblastic pale-red garnet cores record prograde metamorphism; the UHP and initial decompression periods described here are primarily evinced by (1) inclusion-poor colorless garnet rims and omphacite, and (2) sodic augite–plagioclase symplectite, respectively (Fig. DR2) (cf. de Sigoyer et al., 1997; O'Brien, 2006; Konrad-Schmolke et al., 2008). Analyses were obtained from matrix zircon (33% of analyses) and zircon included in UHP garnet (15%), omphacite (49%), and other phases (3%) (Fig. DR2; Table DR1). Cathodoluminescence images of zircons in both samples reveal complex zoning indicating protracted zircon growth (Fig. DR3). Zircons in both samples are typically 12–30 μm across, necessitating a laser spot size of ~12–14 μm. Because of the small laser spot size, the uncertainty on the $^{206}Pb/^{238}U$ ratio of the secondary standards was 5%; this error was added in quadrature to each analysis.

U-Pb isotopic results (Table DR1) are reported in Tera-Wasserburg concordia plots (Fig. 2) as well as histograms and relative probability functions of ^{207}Pb-corrected dates (Ludwig, 2009) (Fig. 3). REE data are plotted as chondrite-normalized values (Fig. 4) and reported in Table DR2. Because the analyzed zircons are small and have low U concentrations (median value = 53 ppm), the radiogenic/common Pb ratios are relatively low. As a consequence, each sample yields an array of analyses distributed between common Pb ($^{207}Pb/^{206}Pb$ = 0.838 for CM71710–4, and 0.806 for DD71710–2b) and concordia. The samples have low Th/U ratios (≤0.35) and similar individual REE patterns. ^{207}Pb-corrected dates for CM71710–4 and DD71710–2b span ca. 53–37 Ma, peaking at ca. 47–43 Ma (Fig. 3). The mean square of weighted deviates (MSWD) values of the weighted mean dates for CM71710–4 (45.3 ± 1.6 Ma, MSWD = 3.4, n = 47) and DD71710–2b (44.2 ± 1.2 Ma, MSWD = 2.4, n = 61) (Fig. 2) indicate that the analyses do not represent single populations. Aside from a few anomalies, the REE patterns for both samples display similar characteristics, a distinct lack of a Eu anomaly and flat heavy REE slopes (Fig. 4).

DISCUSSION AND CONCLUSIONS

The ca. 53–37 Ma range and ca. 47–43 Ma peak of ^{207}Pb-corrected dates of the 108 U-Pb zircon analyses (Fig. 3) represent protracted zircon growth or recrystallization. This is demonstrated by the elevated MSWD values for the weighted mean date of both samples (Fig. 2) and the complex zircon zoning patterns (Fig. DR3). Most of the dates likely reflect UHP and/or prograde zircon (re)crystallization because (1) the REE data indicate (re)crystallization in the presence of garnet and absence of plagioclase (Fig. 4; Table DR2), and (2) 64% of the dates were obtained from zircon included in garnet and omphacite (Fig. DR2; Table DR1). The zircon dates are not correlated with their textural setting (e.g., as matrix grains or included grains) (Fig. DR4). We interpret the upper limit of the date peak (i.e., ca. 47 Ma) as the oldest age of UHP metamorphism at Tso Morari, which is also reflected and overlain by the age obtained

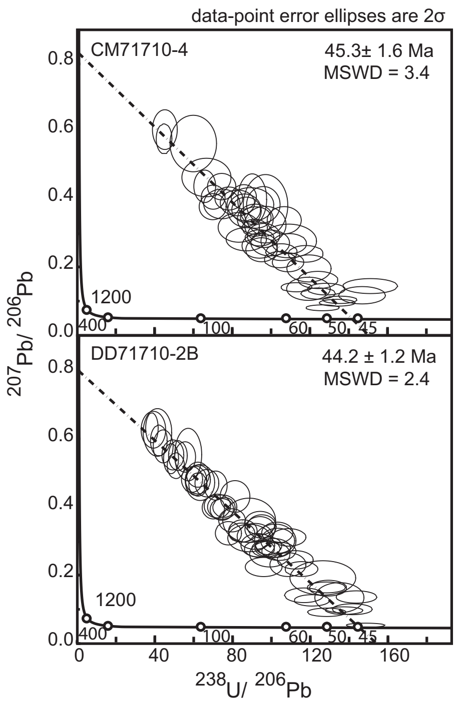

Figure 2. Zircon isochron dates. Tera-Wasserburg concordia plots of U-Pb data uncorrected for common Pb. Lower intercept dates of best-fit lines through all data are noted in the upper right. MSWD—mean square of weighted deviates.

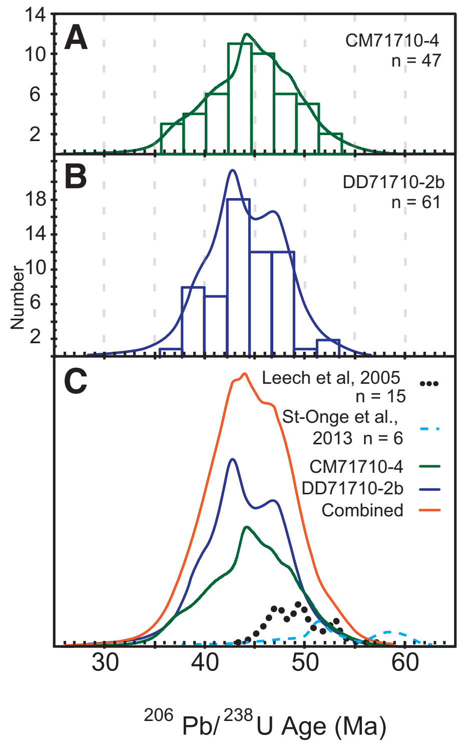

Figure 3. U-Pb zircon dates. Probability density functions (PDFs) and histograms of $^{238}U/^{206}Pb$ dates (^{207}Pb-corrected). All dates are concordia lower intercept dates along the line extending from common Pb through each datum. A: Sample CM71710–4. Green line is PDF curve, n is number of analyses, histogram bin size is 2 Ma. Assumed value for common $^{207}Pb/^{206}Pb$ = 0.838 is taken from the fit in Figure 2, and is indistinguishable from the Stacey-Kramers (1975) model value. B: Sample DD71710–2b. Blue line is PDF curve, n is number of analyses, histogram bin size is 2 Ma, common $^{207}Pb/^{206}Pb$ = 0.806 (using the Stacey-Kramers model value of 0.838 changes the spot dates by an average of <1.6 m.y.). C: PDFs for both samples, individually and combined (orange curve), for sample T38 from Leech et al. (2005) (dotted line, n = 15), and for zircons analyzed in mafic eclogite sample L08–03A from St-Onge et al. (2013) (light-blue dotted curve).

[1]GSA Data Repository item 2013233, Figures DR1–DR4, and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

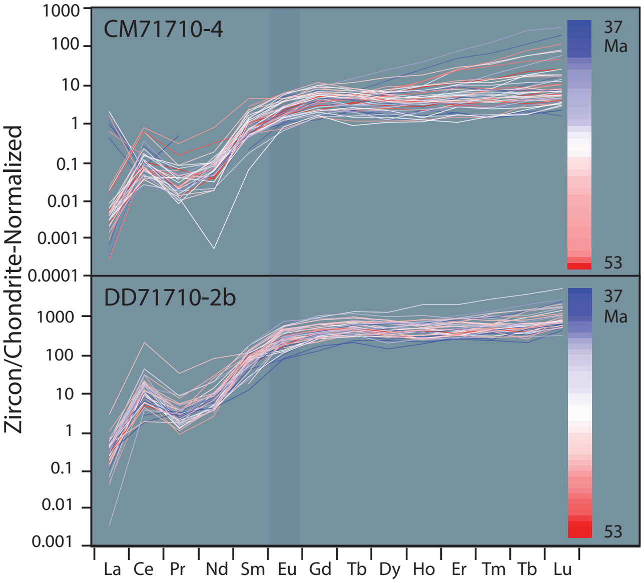

Figure 4. Rare earth element diagrams. Colors represent associated U-Pb date. Blue dates are older, red are younger.

from zircon inclusions form UHP garnet rims (46.2 ± 2.6 Ma; Kaneko et al., 2003).

The much smaller Kaghan Valley data set reported by Kaneko et al. (2003) has coesite included in zircon rims with a Tera-Wasserburg intercept age of 45.9 ± 0.73 Ma (MSWD = 2.3, n = 8). The remarkable similarity in the geochronologic data between the Tso Morari and Kaghan Valley eclogites, coupled with the coesite inclusion record from Kaneko et al. (2003) and the REE chemistry and textures of the Tso Morari zircons, indicates generally synchronous subduction of the two Himalayan UHP sites. Eclogite-facies metamorphism lasted from ca. 47 Ma to 43 Ma. This eliminates the need to explain a >5 m.y. difference in UHP timing using models featuring multiple accretion events or an irregular northern margin of India (e.g., Guillot et al., 2007; White and Lister, 2012). If UHP metamorphism occurs along the leading edge of a continental margin, it will postdate initial continent subduction by ~1–4 m.y., depending on convergence velocity and subducting slab dip (Kaneko et al., 2003; Guillot et al., 2004; Leech et al., 2005; Table DR3). Therefore, the Himalayan UHP record is consistent with initiation of Indian subduction at 51–47 Ma.

The timing of the India-Asia collision initiation is a key parameter for models of Himalayan-Tibetan orogenic evolution (e.g., Beaumont et al., 2001), post-collisional shortening estimates from plate-circuit reconstructions (van Hinsbergen et al., 2011b), tectonics-linked climatic shifts (Raymo and Ruddiman, 1992; Kutzbach and Ruddiman, 1993), drainage evolution of Asian river systems (Brookfield, 1998), paleo-ocean water chemistry and currents (Garzanti et al., 1987; Raymo et al., 1988; Beck et al., 1998), and faunal exchange between the continents (Clyde et al., 2003). The proposed ages of the initiation of collision range from 70 Ma to 35 Ma (see reviews discussed herein), and it is possible that multiple continental fragments were accreted during this time (White and Lister, 2012; van Hinsbergen et al., 2012). All of the evidence for a pre-50 Ma collision can be interpreted to record arc accretion (e.g., Cai et al., 2011; van Hinsbergen et al., 2011b). Initial collision as young as 35 Ma is precluded by plate-circuit reconstructions (Dupont-Nivet et al., 2010; van Hinsbergen et al., 2011a). A ca. 50 Ma India-Asia collision is supported by the cessation of marine sedimentation, paleomagnetic reconstructions, the deposition of Asia-sourced sediment on the Indian plate, and mixing of Indian and Asian detritus (Zhu et al., 2005; Najman et al., 2010; van Hinsbergen et al., 2011b; Wang et al., 2011). Previous interpretations of Himalayan UHP metamorphism involved an ~6 m.y. interregnum between a 53–51 Ma event at Tso Morari and a ca. 46 Ma event at Kaghan Valley (Kaneko et al., 2003; Leech et al., 2005, St-Onge et al., 2013) that was interpreted to reflect continental subduction of a jagged Indian margin (Guillot et al., 2007) or separate accretion events (White and Lister, 2012). Our documentation of a single phase of eclogite facies metamorphism at these two localities separated by ~450 km instead is consistent with the initiation of northwest India-Asia collision synchronously along the margin at ca. 50 Ma.

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