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The onset of India–Asia continental collision: Early, steep subduction required by the timing of UHP metamorphism in the western Himalaya

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Abstract

Ultrahigh-pressure (UHP) rocks in the NW Himalaya are some of the youngest on Earth, and allow testing of critical questions of UHP formation and exhumation and the timing of the India–Asia collision. Initial collision of India with Asia is widely cited as being at 55 ± 1 Ma based on a paleomagnetically determined slowdown of India's plate velocity, and as being at ca. 51 Ma based on the termination of marine carbonate deposition. Even relatively small changes in this collision age force large changes in tectonic reconstructions because of the rapid India–Asia convergence rate of 134 mm/a at the time of collision. New U–Pb SHRIMP dating of zircon shows that Indian rocks of the Tso Morari Complex reached UHP depths at 53.3 ± 0.7 Ma. Given the high rate of Indian subduction, this dating implies that Indian continental crust arrived at the Asian trench no later than 57 ± 1 Ma, providing a metamorphic age for comparison with previous paleomagnetic and stratigraphic estimates. India's collision with Asia may be compared to modern processes in the Timor region in which initiation of collision precedes both the slowing of the convergence rate and the termination of marine carbonate deposition. The Indian UHP rocks must have traveled rapidly along a short, hence steep, path into the mantle. Early continental subduction was at a steep angle, probably vertical, comparable to modern continental subduction in the Hindu Kush, despite evidence for modern-day low-angle subduction of India beneath Tibet. Oceanic slab break-off likely coincided with exhumation of UHP terranes in the western Himalaya and led to the initiation of low-angle subduction and leucogranite generation.

Keywords: western Himalaya; Tibet; ultrahigh-pressure metamorphism; India–Asia collision; Tso Morari Complex; subduction model

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1. Introduction

Ultrahigh-pressure (UHP) metamorphism, demonstrated by the index mineral coesite (a high-pressure polymorph of quartz) that requires a minimum depth of 90 km for its formation, is now widely known from continental collision zones [1–3]. The Tso Morari Complex (TMC) (Fig. 1) underwent UHP metamorphism during subduction of the Indian continent beneath Asia in the Early Eocene. The coesite-bearing UHP eclogites from Tso Morari, India, and Kaghan, Pakistan (e.g., [8,9]), are evidence that the leading edge of the entire northwestern part of the Indian continental margin was subducted beneath the Kohistan–Ladakh arc to a minimum depth of 90 km. Tentative evidence for coexisting coesite and carbonate phases in the TMC

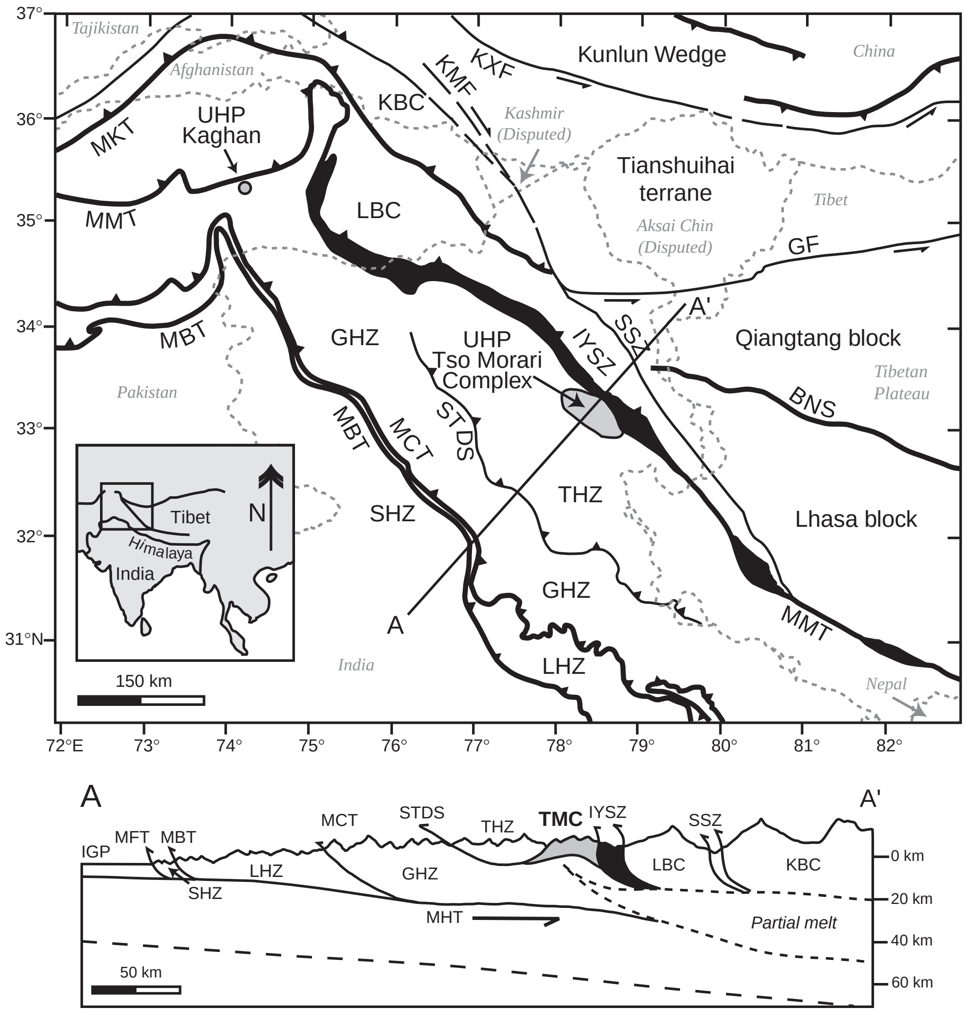


Fig. 1. Regional tectonic map of the western Himalaya showing the Tso Morari Complex (pale gray) and the Indus–Yarlung suture zone (dark gray) (adapted from [4–7]). Simplified modern cross-section A–A′ (modified after [6]; approximate location on map) shows the Tso Morari Complex in the footwall of the Indus–Yarlung suture zone and the ca. 10° modern subduction angle (true scale below sea level; topography is exaggerated). Abbreviations: BNS, Bangong–Nujiang suture; GF, Gozha fault; GHZ, Greater Himalayan zone; IGP, Indo-Gangetic plain; IYSZ, Indus–Yarlung suture zone; KBC, Karakoram batholith complex; KMF, Karakoram fault; KXF, Karakax fault; LBC, Ladakh batholith complex; LHZ, Lesser Himalayan zone; MBT, Main Boundary thrust; MCT, Main Central thrust; MHT, Main Himalayan thrust; MKT, Main Karakoram thrust; MMT, main mantle thrust; SHZ, Sub-Himalayan zone; SSZ, Shyok suture zone; STDS, South Tibetan detachment system; THZ, Tethyan Himalayan zone.

[10] requires subduction of continental rocks to a depth of at least 130 km. Previously published age estimates for UHP metamorphism for the TMC are based on Sm–Nd, Lu–Hf, and conventional U–$Pb_{allanite}$ dating and have significant errors (55 ± 7 Ma, 55 ± 12 Ma, and 55 ± 17 Ma, respectively [4]), and so do not allow precise analysis of the geologic evolution in such a young mountain belt. New U–Pb SHRIMP dating of zircons from the TMC pinpoints the age of peak UHP metamorphism, and helps resolve the timing of subduction and collision in the northwest Himalaya (Figs. 2 and 3, Table 1).

The observation of continental UHP rocks at the Earth's surface, returned there from depths of greater than 90 km, challenges the perceived difficulty of subducting buoyant continental crust to great depth in the mantle. At present, India subducts beneath southern Tibet at ≤ 10° as defined by seismic profiling in eastern Tibet [11,12]; presumably the buoyancy of the subducting continent prevents steep subduction. The essential uniformity of lithospheric structure along the entire Himalayan arc, at least as far west as the TMC, is demonstrated by multiple gravity [13] and magnetotelluric profiles [14–17]. At subduction angles ≤ 10°, rocks would have to travel ≥ 600 km along the subduction thrust (the Main Himalayan Thrust; Fig. 1) to reach the depth of ca. 100 km that corresponds to UHP metamorphism. In contrast, if the subducting slab rapidly becomes vertical, rocks only need to travel 150–250 km to achieve UHP metamorphism, and UHP metamorphism happens sooner after subduction.

The continent–continent collision is thought to have begun in the northwest part of the Himalaya based on biostratigraphy of collision-related sediments on both sides of the Indus–Tsangpo suture zone and on paleomagnetic data [5,18,19]. The onset of collision of India with Asia is inferred to be at 55 ± 1 Ma from paleomagnetic determination of an abrupt slowdown in the northward velocity of the Indian plate [5,18], and inferred, based on the termination of marine carbonate deposition, to be as recent as 50–51 Ma [19–21]. In contrast, our new dating shows that Indian rocks attained UHP depths at 53.3 ± 0.7 Ma. Even given the fast India–Asia convergence rate of 69 mm/a [5], and assuming that the UHP rocks traveled the shortest, hence steepest, path into the mantle, the initial entry of continental crust into the subduction trench must have pre-dated 55 Ma. The variability of estimates for the timing of onset of the India–Asia collision from different datasets (e.g., paleomagnetically determined slowdown, or stratigraphically determined transition from marine to non-marine deposition) need not imply errors in these datasets but rather that these datasets measure different stages in a complex collision process. Here we provide a new age for the entry of the leading edge of the Indian continent into the Asian trench at 57 ± 1 Ma (we avoid the term "onset of continental collision" as being imprecise), which, as might be expected, precedes the detectable slowdown of the northward motion of India by ca. 2 Myr, which in turn precedes the end of marine carbonate deposition by ca. 4 Myr. By inference, oceanic subduction and early continental subduction were at a steep angle, followed by oceanic slab break-off, rapid exhumation of UHP rocks into the crust, and resumption of continental subduction at the modern low angle.

1.1. Previous estimates for timing and rate of the initial India–Asia collision

Stratigraphic constraints have been used to suggest that Himalayan collision began in the westernmost Himalaya in northern Pakistan at about 52 Ma [19] to 55 Ma [22] and progressed eastward until collision ended by 41 Ma [19] to 50 Ma [23] near the eastern syntaxis. The best constrained estimates for the western Himalaya are based on stratigraphy in the Zanskar region near the TMC, where Early Eocene (50–51 Ma) deltaic red beds contain ophiolitic detritus; marine sedimentation ended by the early Middle Eocene (49–46 Ma) [19,20]. The Lower Eocene deposits contain clear evidence for their source in the northern Himalayan thrust belt, implying that orogenesis had already begun by the Early Eocene ([23] and references therein).

In this paper, we adopt the recent comprehensive analysis of the age of collision in the northwestern Himalaya by Guillot et al. [5], noting that this is built on much earlier work spanning discussions as diverse as paleomagnetic data (e.g., [18]) and stratigraphy (e.g., [19–21]). The initial continental collision of India with Asia is recognized paleomagnetically as a sudden slowing from 180 ± 50 mm/a to 134 ± 33 mm/a of the northward motion of India no later than 55 Ma [5,18]. We follow Guillot et al. [5] in asserting that the

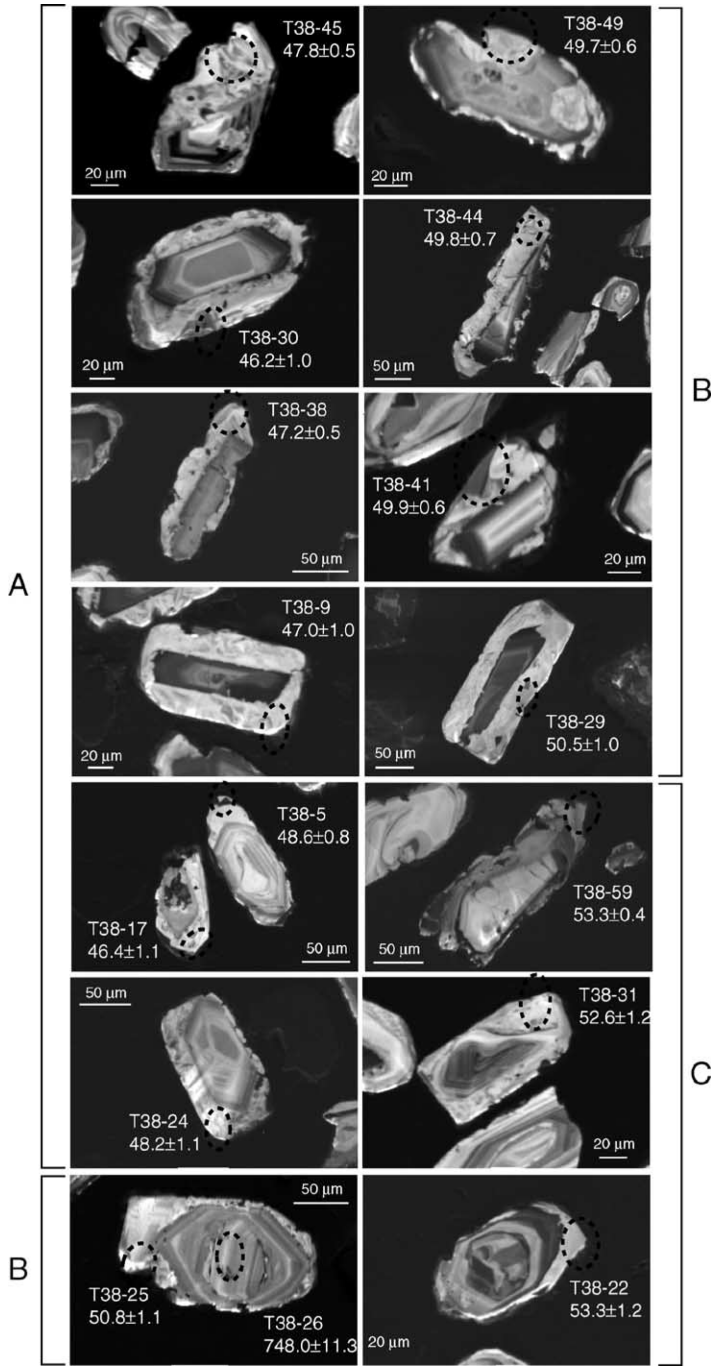


Fig. 2. Cathodoluminescence images of Tso Morari zircons showing individual SHRIMP analysis spots. (A) Seven zircons used in weighted average yielding 47.5±0.5 Ma age. (B) Five zircons used in weighted average yielding 50.0±0.6 Ma age. (C) Three zircons used in weighted average yielding 53.3±0.7 Ma age.

Table 1
Concordant Eocene SHRIMP U–Pb analyses of zircon from the Tso Morari Complex

Analysis spot	U (ppm)	Th (ppm)	Th/U	$^{204}Pb/^{206}Pb$	Common ^{206}Pb (%)	$^{238}U/^{206}Pb^a$	$^{207}Pb/^{206}Pb^a$	$^{207}Pb/^{235}U^b$	Metamorphic facies	$^{206}Pb/^{238}U^c$ (Ma)
T38-5	1411	10	0.01	0.0006	0.7	17.2124 ± 1.4711	0.0569 ± 1.5485	0.0453 ± 13.0028	Amphibolite	48.6 ± 0.8
T38-9	408	5	0.01	0.0000	0.9	14.4942 ± 2.4568	0.0578 ± 6.2480	0.0552 ± 7.0892	Amphibolite	47.0 ± 1.0
T38-17	508	2	0.00	0.0025	2.2	18.5901 ± 1.4025	0.0568 ± 1.2363	0.0263 ± 50.7294	Amphibolite	46.4 ± 1.1
T38-22	493	4	0.01	0.0030	1.4	131.6984 ± 2.1081	0.0567 ± 10.0734	–	UHP	53.3 ± 1.2
T38-24	424	1	0.00	0.0000	1.2	8.1187 ± 1.5489	0.0651 ± 1.7870	0.0594 ± 10.2917	Amphibolite	48.2 ± 1.1
T38-25	507	3	0.01	0.0028	3.0	3.2254 ± 1.4201	0.1051 ± 0.5420	0.0301 ± 55.9327	Eclogite	50.8 ± 1.1
T38-29	370	2	0.01	0.0009	2.8	118.4879 ± 2.1024	0.0705 ± 5.5458	0.0620 ± 10.1119	Eclogite	50.5 ± 1.0
T38-30	599	3	0.00	0.0000	1.9	92.6446 ± 1.9171	0.2682 ± 2.8124	0.0629 ± 6.4790	Amphibolite	46.2 ± 1.0
T38-31	440	45	0.10	0.0028	3.0	14.1134 ± 0.3652	0.0571 ± 1.2060	0.0308 ± 80.1297	UHP	52.6 ± 1.2
T38-38	562	8	0.01	0.0039	7.0	15.6648 ± 0.3388	0.0583 ± 1.1535	0.0679 ± 72.0415	Amphibolite	47.2 ± 0.5
T38-41	961	2	0.00	0.0016	3.0	150.3122 ± 0.9567	0.0628 ± 3.8523	0.0404 ± 19.4544	Eclogite	49.9 ± 0.7
T38-44	336	1	0.00	0.0015	2.8	123.0497 ± 0.9423	0.0961 ± 3.0535	0.0532 ± 21.1635	Eclogite	49.8 ± 0.7
T38-45	419	2	0.00	0.0006	1.1	87.6734 ± 0.8520	0.0584 ± 3.4805	0.0446 ± 12.1739	Amphibolite	47.8 ± 0.5
T38-49	872	7	0.01	0.0067	12.2	69.1642 ± 0.8252	0.0704 ± 3.0476	–	Eclogite	49.7 ± 0.6
T38-59	836	5	0.01	0.0029	5.3	23.8414 ± 1.2700	0.0566 ± 1.3510	0.0220 ± 57.5181	UHP	53.3 ± 0.4

Note: 1σ error, unless noted otherwise.
[a] Uncorrected; error given as percentage.
[b] Corrected for ^{204}Pb; error given as percentage.
[c] Age corrected for ^{207}Pb.

termination of marine sedimentation is a delayed response to the initial contact between the Indian and Asian continents.

Guillot et al. [5] reviewed paleomagnetic data, mass-balanced cross-sections, continental reconstructions, and tomographic data to derive a self-consistent model in which, immediately after the first continental contact from 55 to 50 Ma, a total India–Asia plate convergence rate of 134 mm/a is comprised of a continental subduction rate (including Himalayan shortening) of 69 mm/a and an Asian shortening rate of 65 mm/a. Given the error bounds on this estimate, and the likelihood that these rates were all continuously diminishing with time, we use their subduction rate (69 mm/a) to estimate the time between initial contact and UHP metamorphism (Table 2), even though our estimated ages of first contact are in the range 56–58 Ma.

1.2. The UHP Tso Morari Complex

The TMC is a 100 × 50 km UHP subduction zone complex in eastern Ladakh near the western syntaxis of the Himalaya, south of the Indus–Yarlung suture zone (IYSZ) (Fig. 1). The TMC [24,25] is comprised of dominantly Proterozoic to Paleozoic quartzofeldspathic orthogneiss and metasedimentary rocks, Paleozoic intrusive granitoids, and rare, small eclogite bodies and their retrogressed equivalents [5,6,26–28]. The eclogites have isotopic and geochemical affinities to, and are thought to represent metamorphosed equivalents of, the intracontinental Permian Panjal traps [4,29]. The TMC forms an elongate NW-plunging dome that is tectonically bound by the IYSZ along its entire northeastern margin and by the Tethyan Himalayan zone along its southwestern margin [6,30].

Coesite occurs in the TMC as inclusions in garnet in eclogite [31]. Peak *P–T* conditions for the UHP eclogite and eclogite-facies gneisses in the TMC were 750–850 °C and a minimum of 2.7–3.9 GPa based on conventional thermobarometric calculations, Thermocalc estimates [32], the minimum pressure for coesite formation ([6] and references therein), and the presence of co-existing coesite and carbonate phases [10]. Retrograde HP eclogite-facies (2.0 GPa, 600 °C) and amphibolite-facies metamorphism (1.3 GPa, 600 °C) were followed by greenschist-facies metamorphism (0.4 GPa, 350 °C) and final exhumation to the upper crust [4,6,33]. As in other UHP complexes, the *P–T–t* paths for Tso Morari host gneisses and eclogites are similar, indicating that they experienced the same tectonometamorphic history [1,3,26]; hence

Table 2
Parameters used in calculations based on the geometry detailed in Fig. 5

Model	R (km)	Z_1 (km)	Z_2 (km)	Z_3 (km)	Z_4 (km)	θ_1 (°)	$\theta_1+\theta_2$ (°)	L_1 (km)	L_2 (km)	L_1+L_2 (km)	T (Myr)	Collision age using 53.3 Ma UHPM date (Ma)	Collision age using minimum UHPM age of 52.6 Ma (Ma)	Collision age using maximum UHPM age of 54.0 Ma (Ma)
Preferred model based on most likely geometric assumptions														
1	350	15	2	100	1	6.0	41	37	211	248	3.1	56.4	55.7	57.1
Preferred model assuming subduction to 130 km (~3.9 GPa)														
2	350	15	2	130	1	6.0	48	37	254	291	3.7	57.0	56.3	57.7
Model based on bending radius of oceanic crust—minimum possible time to UHP depths														
3	150	20	3	90	2	10.8	57	28	121	149	1.7	55.0	54.3	55.7
Geometric assumptions chosen to give a minimum likely subduction time and distance														
4	250	20	3	90	2	8.5	43	37	152	189	2.2	55.5	54.8	56.2
Geometric assumptions chosen to maximize subduction time and distance														
5	450	5	1	130	1	3.8	44	30	312	342	4.5	57.8	57.1	58.5

R, radius of curvature; Z_1, TMC depth in the Indian crust; Z_2, trench depth; Z_3, minimum depth of UHP metamorphism; Z_4, Asian topography; θ_1, dip of subducting slab at trench; $\theta_1+\theta_2$, dip of subducting slab at UHP depth; L_1, distance from horizontal to trench; L_2, amount of subducted Indian crust from trench to UHP depth; T, time to minimum UHP depth from entry into the subduction trench using 69 mm/a convergence rate; UHP metamorphism (UHPM) ages are based on our 53.3 ± 0.7 Ma date.

the eclogites are not exotic tectonic slices added to the TMC during convergence and/or exhumation.

2. New U–Pb zircon SHRIMP data

The 78 zircons dated in this study come from a quartzofeldspathic gneiss (sample T38 [78°21′33″E, 33°9′5″N]) from host quartzofeldspathic gneiss to eclogite. Zircons were separated and mounted using standard sample preparation methods for ion microprobe analysis [34], and U–Pb SHRIMP analyses and data reduction using Isoplot following standard techniques [34,35]. Zircons include both sub-rounded and irregular-shaped grains that display clear core/rim zoning relationships under cathodoluminescence (CL) (Fig. 2). Some zircon cores yield Proterozoic ages (748 ± 11 to 1744 ± 24 Ma), but most cores and mantles yield Ordovician ages (462 ± 9 to 477 ± 10 Ma). Analyses that yielded Eocene ages (Figs. 2 and 3, Table 1) were from light-colored rims with darker mantles/cores with distinctive igneous oscillatory zoning; these metamorphic rims had very low Th/U ratios (< 0.14 with most < 0.02).

A trimodal distribution of the concordant metamorphic rim ages from 15 zircons (Fig. 2) indicates three separate events in the Early Eocene between about 46 and 53 Ma (Fig. 3). Weighted mean averages of zircon rim analyses for the oldest and youngest events yield 53.3 ± 0.7 Ma (three spots) for the UHP event and 47.5 ± 0.5 Ma (seven spots) corresponding to the amphibolite-facies retrograde event (Fig. 3). These two new U–Pb SHRIMP ages correspond well to two groups of existing thermochronometric data for the UHP and amphibolite-facies events in the TMC at ca. 55 ± 11 Ma (Sm–Nd, Lu–Hf, and $U–Pb_{allanite}$) and 47 ± 3 Ma (Ar–Ar, Sm–Nd, and Rb–Sr), respectively [4], further supporting our interpretation. The intermediate peak at 50.0 ± 0.6 Ma (five spots) likely records an HP eclogite-facies event that is reflected in thermobarometric calculations (see [4,6,27]) and falls on the exhumation path between the UHP and amphibolite-facies events. A thorough discussion of this new U–Pb dating appears in Leech et al. [36]. The TMC was rapidly exhumed from ≥ 90 km at 53.3 Ma to paleodepths ≤ 66 km by 50.0 Ma and ≤ 43 km by 47.5 Ma, as documented by these SHRIMP ages, and thermobarometry and isotopic system closure temperatures [4,6]. The exhumed UHP slices returned buoyant continental crust to the surface along the subduction zone.

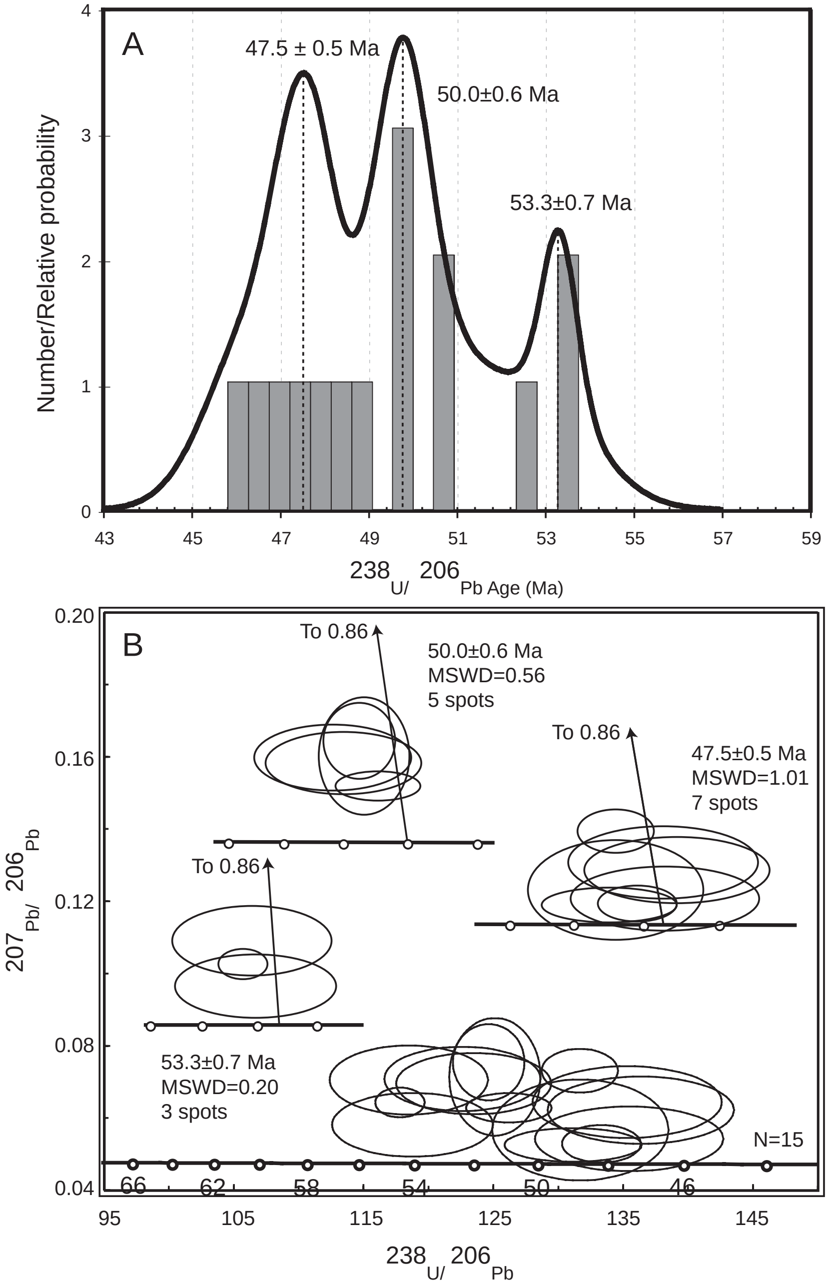


Fig. 3. Eocene U–Pb SHRIMP data for Tso Morari sample T38. (A) Cumulative probability curve and histogram for the same $^{238}U/^{206}Pb$ ages (^{207}Pb-corrected). Trimodal curve indicates three zircon populations at ca. 47, 50, and 53 Ma. (B) Tera–Wasserburg concordia diagram for zircons with ages between 46 and 53 Ma (error ellipses are 2σ); data are uncorrected for common Pb; all data shown are greater than 95% concordant (discordance was estimated by using a mixing line between the common Pb ratio [$^{207}Pb/^{206}Pb$=0.86] and concordia), and analyses high in common Pb were excluded.

3. Previous estimates of subduction dip

Other authors have attempted to calculate the dip of the Indian slab based on older geochronologic data in the western Himalaya [8,37] but have done so using oversimplified models of uniform slab dip that lack predictive value because they are physically unrealistic and because they require that one assumes the age of initial collision (Fig. 4A). Thus, Kaneko et al. [8] dated UHP metamorphism of the Kaghan eclogites at 46 Ma then assumed that India collided with Asia at 55–53 Ma, subducted at 45 mm/a, and was metamorphosed at 100 km depth. Permitting

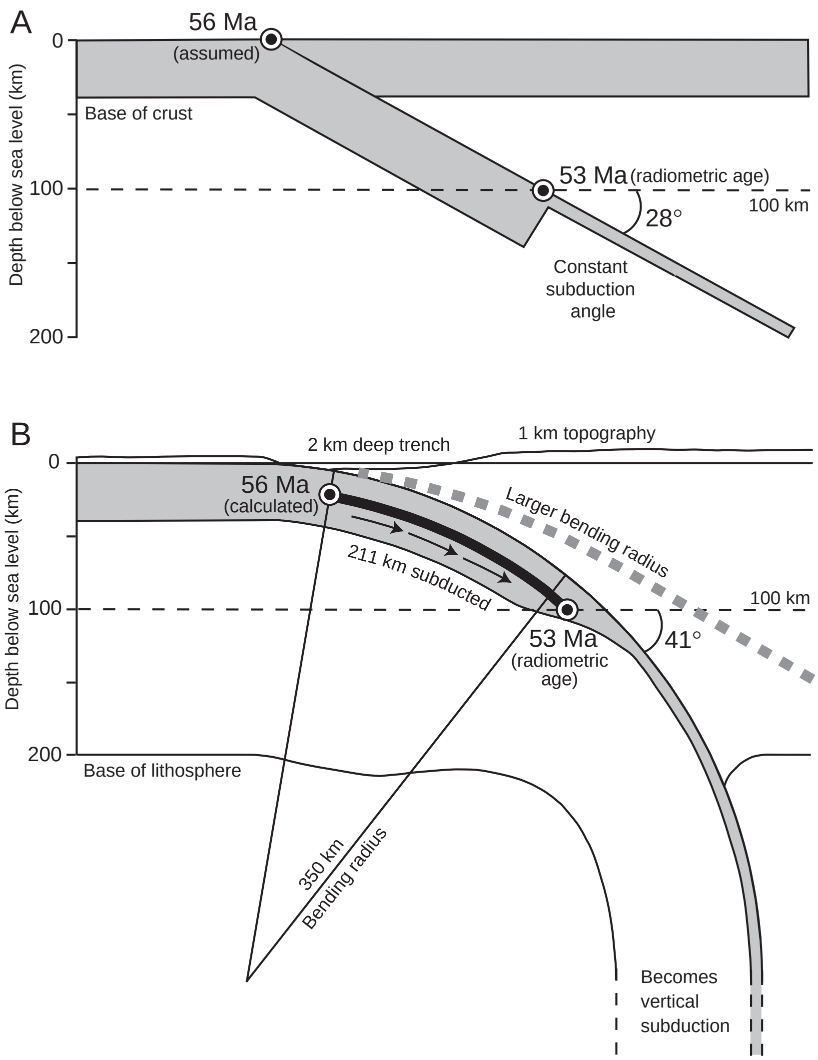


Fig. 4. (A) Simplistic model of planar subduction underestimates the angle of the subducting slab, and requires specifying ages for the India–Asia collision and UHP metamorphism. (B) More realistic model includes bending of the lithosphere and predicts the age of the India–Asia collision (Fig. 5 and Table 2); model shown uses 350-km bending radius of continental lithosphere [40,41]. Any larger bending radius or shallower subduction angle (dashed gray line) greatly increases the amount of lithosphere that must be subducted and the time between collision and UHP metamorphism. Ages and angles are from Model 1, Table 2. Solid black line represents the subduction path; bull's-eye follows the TMC protolith at 15 km depth in the Indian crust to 100 km depth where coesite crystallizes. Topography above sea level and trench depth are exaggerated.

infinitely sharp bending of continental crust and using a planar subduction geometry, Kaneko et al. used the simple equation:

$$\text{Slab dip} = \sin^{-1}\left[\frac{\text{Depth of UHP metamorphism}}{(\text{Age of collision} - \text{Age of UHP metamorphism}) \times \text{Convergence rate}}\right]$$

to infer a slab dip of 14–19°. Similarly, Guillot et al. [37] took an age of 54 Ma (presumably based on 55 ± 11 Ma in [4]) for the UHP metamorphism of the TMC, then assumed that India collided with Asia at 57 Ma, subducted at 70 mm/a, and was metamorphosed at 100 km depth, to infer a slab dip of 28°. These simplistic models (1) assume that continental crust can bend infinitely sharply (has zero strength); (2) assume a fixed time for the initial collision; (3) under-predict the dip angle of subducting Indian continental crust at the time of UHP metamorphism; and (4) under-predict the maximum dip angle of the preceding subducting oceanic crust. Error (2) above may perpetuate an incorrect date for initial India–Asia collision. Error (3) provides an incorrect dip angle for comparison with other models of subduction, slab break-off, and exhumation (e.g., [38]). Error (4) provides an incorrect slab angle for comparison with tomographic images inferred to represent subducted Tethyan crust (e.g., [39]). A more physically correct model, in which the lithosphere has a finite bending radius, provides a more realistic subduction geometry and predicts (instead of assuming) the age of initial collision (Fig. 4B). This model makes very different predictions from the simplistic planar-slab model: for the 3 Myr delay between collision and metamorphism assumed by Guillot et al. [37], the planar-slab model predicts a dip of 28° everywhere (Fig. 4A); in contrast, the curved-slab model predicts a dip of ca. 41° at the point of UHP metamorphism and 90° (vertical) at great depth (Fig. 4B).

4. From collision to UHP metamorphism

Our precise date for UHP metamorphism in the TMC (53.3 ± 0.7 Ma) is surprisingly close to the widely cited paleomagnetic age of collision of India with Asia (55 ± 1 Ma). We calculate the minimum time possible between the first entry of Indian continental crust into the subduction zone and the onset of UHP metamorphism in the TMC. For all reasonable assumptions, oceanic crust at the leading edge of India must have been subducting near-vertically, and the leading edge of the Indian continent must have been bent into the tightest possible radius of curvature in this steeply dipping subduction zone.

4.1. Model parameters

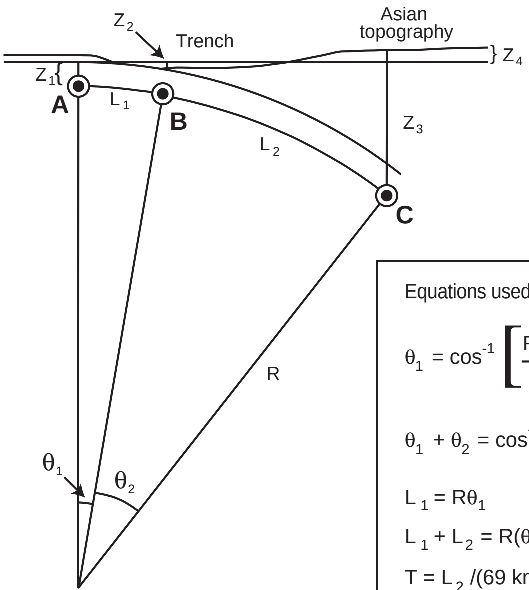
The TMC represents continental crust as attested by the Paleozoic quartzofeldspathic gneisses containing inherited Proterozoic zircons. The time between collision and UHP metamorphism is minimized if the TMC represents the leading edge of continental India. The minimum pressure at which UHP metamorphism can occur is 2.7 GPa [42] based on the quartz–coesite transition (equivalent to a minimum 90 km depth). It is likely that the TMC was subducted beyond this minimum depth for UHP metamorphism (at least to 100 km) because large coesite grains are preserved, suggesting that the rocks were well within the coesite stability field; there is also mineralogical evidence for even deeper subduction to ca. 130 km based on coexisting coesite and carbonate phases [10].

A likely initial depth for the TMC protolith is 15 km, in the mid-crust; a likely minimum depth of the subduction trench below sea level is 2 km based on the Timor trough where the leading edge of Australia has been overridden by the Banda forearc [43]; and a likely maximum topography above the site of UHP metamorphism is 1 km during early stages of collision [44] (Fig. 4B). Another key parameter is the radius of curvature of the Indian lithosphere bending into the subduction zone. The most sharply curved modern Benioff zones have radii of curvature of 150–200 km where dense, cold oceanic crust is subducting (e.g., New Hebrides [45] and Marianas [46]). Continental lithosphere is thicker and has a larger bending radius (e.g., ca. 350 km in the Pamirs/Hindu Kush [40,41,47]).

4.2. Amounts of subducted Indian lithosphere and time to UHP metamorphism

The geometry of the subduction zone and the rate of convergence (69 mm/a immediately following collision) can be used to calculate the time between the initial collision and UHP metamorphism (Figs. 4B and 5, Table 2). Models (1)–(5) (Table 2) test parameter configurations to show the likely minimum and maximum time from collision to UHP metamorphism. Models (1) and (2) use different metamorphic depths (100 km and 130 km) for the preferred model, with the most likely values for all other variables, and require 211 km and 254 km of convergence taking 3–4 Myr (Fig. 4B, Table 2). The time from collision to UHP metamorphism can be decreased by choosing the smallest possible radius of curvature (150 km for oceanic crust), increasing the initial depth of the TMC protolith, and using the minimum depth for UHP metamorphism (90 km); model (3) shows that it would take a minimum of 1.7 Myr to reach UHP depths. Model (4) maintains the parameters of model (3) but uses the smallest likely radius of curvature for continental crust, this giving us a more likely minimum time (2.2 Myr) to UHP depths. Any radius of bending greater than 150 km, or subduction to depths greater than the absolute minimum of 90 km [42], increases the required amount of convergence and requires more time from the initial collision of India with Asia to UHP metamorphism. Model (5) increases the time to UHP metamorphism to 4.5 Myr by increasing the radius of curvature to 450 km, decreasing the initial depth of the TMC protolith, and increasing the depth of UHP metamorphism to 130 km.

Preferred models (1) and (2) require 3–4 Myr to subduct the TMC to UHP depths (Table 2). Because UHP metamorphism occurred at 53.3 ± 0.7 Ma (Fig. 3), we infer that initial contact of Indian continental crust with Asian forearc crust occurred between 56 and 58 Ma. This best estimate for the age of collision is 2–5 Myr older than previously inferred stratigraphically [19,22] and 1–3 Myr older than previously inferred paleomagnetically [18]. Every 1 Myr added to the collision age requires Greater India and Asia to each have been ca. 65–70 km broader to accommodate the greater convergence achieved in the longer time since collision. Even these significant differences are less than the uncertainties in the paleomagnetically determined positions of the leading edges of India and Asia at the time of collision (e.g., [22]). The size of



Equations used in Table 2 based on this diagram:

$$\theta_1 = \cos^{-1}\left[\frac{R + Z_1 - Z_2}{R + Z_1}\right]$$

$$\theta_1 + \theta_2 = \cos^{-1}\left[\frac{R + Z_1 - Z_3 + Z_4}{R}\right]$$

$$L_1 = R\theta_1$$

$$L_1 + L_2 = R(\theta_1 + \theta_2)$$

$$T = L_2/(69\ \text{km/Ma})$$

Fig. 5. Geometry of the India–Asia paleo-subduction zone. Bull's-eye follows the TMC protolith at 15 km depth in the Indian crust from horizontal (A) to the onset of collision between India and Asia (B) to UHP metamorphism at 100 km depth (C).

Greater India and Asia would be reduced if one were to postulate that the peak UHP event represents subduction of the TMC beneath an arc or marginal ocean south of the Asian continent (as opposed to the Asian continent itself, cf. the origin of HP eclogites beneath the Semail ophiolite in Oman [48]), but the only plausible candidate arc and ophiolite in the Ladakh region (Spong arc, Spontang ophiolite) are the wrong ages, having completed obduction prior to 65 Ma [49]. Instead in our model, in order to subduct the TMC as rapidly as possible and to have Indian continental crust arrive at the subduction zone only ca. 2 Myr before the paleomagnetically determined slowdown of India (to avoid forcing the initial collision age back further), the Indian slab must become vertical at depth. Note, however, that the subduction angle of Indian continental crust at the depth of earliest possible UHP metamorphism (Fig. 4B; $\theta_1-\theta_2$ in Fig. 5; Table 2) was only ca. 40–50°; this is the dip of the subducting slab when the UHP slice broke off and began its exhumation to the surface.

4.3. Sequence of events at the onset of continental collision

The interaction of two continents must be a complex process in space and time. Even the events termed by different authors as "the onset of collision" may span millions of years. The first event that might reasonably be termed continental collision is the first entry of continental crust into the subduction zone, which marks the first physical contact between subducting continental crust and the overriding plate. Inevitably, it then takes some time—based on the chronology presented above, as much as 2 Myr—for the entry of continental crust into the subduction zone to be manifested by a detectable slowdown in convergence velocity, used by some authors to mark the "onset of continental collision." Also inevitably, it takes time before sufficient continental crust has subducted for sufficient compression or buoyancy forces to develop to uplift the overriding shelf sufficiently to end marine sedimentation, and to replace it with syncollisional, sub-aerial sedimentation, the stratigraphic marker used by other authors to mark the "onset of continental collision" (e.g., [19–21]).

A comparison with the modern-day analogue of the collision of Australia with Indonesia provides valuable insight. The main continental margin of Australia entered the Banda Trench (eastern Java Trench) by about 3 Ma (e.g., [43,50]), and complex structural and tectonic features regarded as marking the Australia–Asia collision include both uplift and subsidence in different parts of the Australian shelf [51]. Despite the record of 3 Myr of continental subduction, shallow marine carbonate deposition continued through the Quaternary and continues today on the Sahul Shelf north of Australia [52]. Thus, the stratigraphic marker taken by Rowley [19] and others to represent the "onset of continental collision" in the India–Asia collision will post-date the arrival of continental crust at the Java Trench by more than 3 Myr in the Timor region.

5. Two-stage development of Tibet and the Himalaya

Some geodynamic reconstructions of the India–Asia collision show early, steep subduction of lithosphere [5,22], arguing from tomographic data [39] and analog experiments [38]. It has also been claimed that UHP metamorphism requires steep subduction [47,53] to permit the rapid return of UHP rocks to the surface, thereby preserving their high-pressure/low-temperature mineralogy. Our model attempts to quantify the timing and dip angle of this early, steep subduction of India. Because the modern subduction angle of Indian crust beneath southern Tibet is $\leq 10°$ as demonstrated by seismic profiling [11,12], the India–Asia collision involved two distinct stages: early, steep subduction followed by shallow-angle continental subduction.

To constrain the timing of the transition from steep to shallow subduction, we follow Kohn and Parkinson [54] in ascribing exhumation of the TMC complex to break off of the Tethyan oceanic slab. Because the Kaghan UHP rocks, 450 km west of the TMC, are dated at 46 Ma [8], we believe steep subduction was ongoing until at least 46 Ma, and that oceanic slab break-off and the end of the steep subduction phase occurred after 46 Ma when Kaghan rocks began exhumation. Kohn and Parkinson [54] argue that oceanic slab break-off occurred at ca. 45 Ma in order to generate potassic volcanism in Tibet by 40 Ma; in contrast, Maheo et al. [55] suggested that break-off did not start until 25 Ma to explain Neogene granitic intrusion in south Tibet.

It has been suggested that the well-known belt of leucogranites in the Greater Himalayan Zone [56] was formed by partial melting within the double-thickness crust of southern Tibet and southward extrusion in a ductile mid-crustal layer [11,57–60]. In this channel flow model, shallow subduction starts before the age of the oldest leucogranites, so the onset of shallow-angle subduction may be dated by the presence of the oldest leucogranites. Although most Himalayan leucogranites are early to middle Miocene, the oldest known crystallized at 32 Ma [56]. In the channel flow model, these leucogranites formed ca. 200–300 km north of their present location [59,60], where seismic and magnetotelluric observations [11,17], heat-flow observations [61,62], and thermal modeling [56] place modern melting. At the plate convergence rate of 69 mm/a immediately after collision [5], it would take 3–4 Myr to underthrust Indian crust 200–300 km from the MCT to the modern location of melting; at more reasonable average convergence rates of 20 mm/a for the period from collision to the present [5,63], it would take 10–15 Myr to reach this same location. We therefore suggest that shallow subduction initiated ca. 10 Myr before the oldest crystallization ages of leucogranites, or by 42 Ma.

6. Discussion

In our models, the TMC represents the extreme leading edge of the Indian continent and was never subducted below ca. 130 km, and the India–Asia collision was underway by 57 ± 1 Ma. If the TMC was not the leading edge, or if it was subducted to > 130 km, then the India–Asia collision would have to be significantly earlier than currently believed. Because the Kaghan UHP eclogites are 7 Myr younger than the TMC UHP eclogites, multiple break-off and exhumation events may have occurred. The distance between the TMC and Kaghan (ca. 450 km; Fig. 1) may give a length scale separating such break-off events, and hence the likely lateral dimension of UHP terranes.

In addition to TMC and Kaghan in the western Himalaya, two additional eclogite localities in Nepal and Tibet [64], not yet thoroughly studied, indicate early, steep subduction in the eastern Himalaya as well and, by inference, along the entire Himalayan arc. The leucogranite belt also spans the Himalayan arc from Ladakh to the eastern Himalaya [56]. Finally, four widely separated magnetotelluric transects show that high electrical conductivity, interpreted as requiring modern partial melts [14–17], extends over 1500 km along the Himalayan arc. This substantial uniformity of geologic and geophysical indicators along the orogen suggests that the model of early, steep subduction followed by shallow subduction has widespread applicability in the Himalaya. Break-off of the oceanic lithosphere happened after 46 Ma, but by about 42 Ma the continental crust was being subducted at a shallow-angle beneath Asia, leading to thickening and partial melting of Tibetan crust, and southward extrusion of the leucogranites that date back to 32 Ma [59,60]. Our new, precise U–Pb SHRIMP ages help demonstrate the requirement for this two-stage development of the Himalaya, and provide new dates for the timing of UHP metamorphism in the TMC (53 Ma) and hence for the initial India–Asia contact (57 ± 1 Ma).

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