When did India–Asia collide and make the Himalaya?

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Critical evaluation and comparison of the available geological and geochronological data from the northern parts of the Himalaya and Trans-Himalaya mountains highlight that these mountains did not initially evolve by the collision of continents of the Indian and Asian plates. Instead, subducted Tethyan oceanic lithosphere in front of the Indian continent melted to produce the calc-alkaline suite of the Shyok–Dras volcanic arc and the Ladakh batholith. Hence, the Indian plate initially subducted beneath and started building up the then existing intra-oceanic island arc. Timing of the first impingement of the Indian and Asia plates has been better constrained at around 57.5 Ma by comparing (i) the bulk ages from the Ladakh batholith (product of partial melting of the Tethyan oceanic lithosphere) with (ii) the subducted continental lithospheric and UHP metamorphosed Indian crust in the Tso Morari, and (iii) biostratigraphy of the youngest marine sedimentation in Zanskar. Thus, the Himalaya witnessed its first rise and emergence from deeply exhumed terrain in the Tso Morari after around 53 Ma, followed by sequential imbrication of the Indian continental lithosphere and associated exhumation during rise of the Himalayan mountains from north to the south since 45 Ma.

Keywords: Batholith, collision of plates, intra-oceanic islands arc, lithosphere.

VARIOUS palaeogeographic reconstructions of India and Asia since Palaeozoic postulated that the vast Palaeo- and Neo-Tethys ocean spanned and separated the southern Asian plate and northern Indian plate margins – the region now constitutes parts of the Himalaya and Trans-Himalayan mountain ranges like Ladakh, the Karakoram Mountains and the vast Tibetian plateau[1–3] (Figure 1 *a*). In a relatively stationary Asian plate reference frame, the Indian plate converged northwards at about 180 ± 50 mm year^{-1} during 80 and 55 Ma and subsequently slowed down to 134 ± 33 mm year^{-1} at the collision not later than 55 Ma (Figure 1 *b*)[4]. This movement coincided with the anti-clockwise rotation of the Indian plate, thereby impinging the Asian plate earlier in the northwest in contrast to its hit in the east[4]. Impingement of the Indian plate even persisted during whole of the Cenozoic and is still an ongoing process. Hence, estimating the timing of the India–Asia impingement/collision is one of the most controversial topics in the Himalayan tectonics, as it is estimated anywhere between 65 and 35 Ma (refs 1, 5–18).

Evidences for the India–Asia collision and its timing are given below.

(i) Palaeomagnetism: Convergence in the northward movement of the Indian plate and its slow-down took place at around 55 ± 1 Ma from the palaeomagnetic anomalies in the Indian ocean[4,7,11].

(ii) Palaeolatitude evidences: The India–Asia suturing of the Tethyan succession in the Himalaya with the Lhasa terrane to the north took place at 46 ± 8 Ma when these terranes started to overlap at 22.8 ± 4.20 N palaeolatitude[19,20].

(iii) Stratigraphy: (a) 56.5–54.9 Ma as the maximum age of initiation of the India–Asia collision, deciphered from termination of continuous marine sedimentation within the Indus Tsangpo Suture Zone (ITSZ) in Ladakh, and 50.5 Ma as the minimum age of closure of the Tethys along the ITSZ[17] or ~ 51 Ma (ref. 21). In this scenario, the Indian continental lithosphere travelled to the ITSZ trench at 58 Ma (ref. 5). (b) Final marine deposition in south Tibet at ≤ 52 Ma as a consequence of initiation of collision and onset of fluvial sedimentation ca. 51 Ma (refs 8, 9); this date was subsequently modified to 50.6 Ma (ref. 15).

(iv) Sedimentology: Closure of the Neo-Tethyan Ocean during earliest India–Asia collisional stage at ~ 56 Ma (ref. 18) is indicated from renewed clastic supply to the Tethys Himalayan margin in Zanskar, fore bulge related uplift, evaporite nodules in the Upper Palaeocene and later red beds having caliche palaeosols[18]. Timing of first arrival of the Asian-derived detritus in the uppermost Tethyan sediments provides another indication of the collision at ~ 50 Ma (ref. 22).

(v) Magmatism: The Trans-Himalayan Ladakh batholith (LB) grew episodically and interruptedly with the very first small pulse at 105–100 Ma and subsequently between 70 and 50 Ma due to melting of subducting Tethyan oceanic lithosphere till 49.8 ± 0.8 Ma to indicate the timing of the India–Asia continental collision[23–26]. This age is now constrained to 50.2 ± 1.5 Ma as the initial collision age of the Kohistan–Ladakh Island Arc (KLA) with India along ITSZ, and the final collision between the assembled India/Arc and Asia ~ 10 Ma later at

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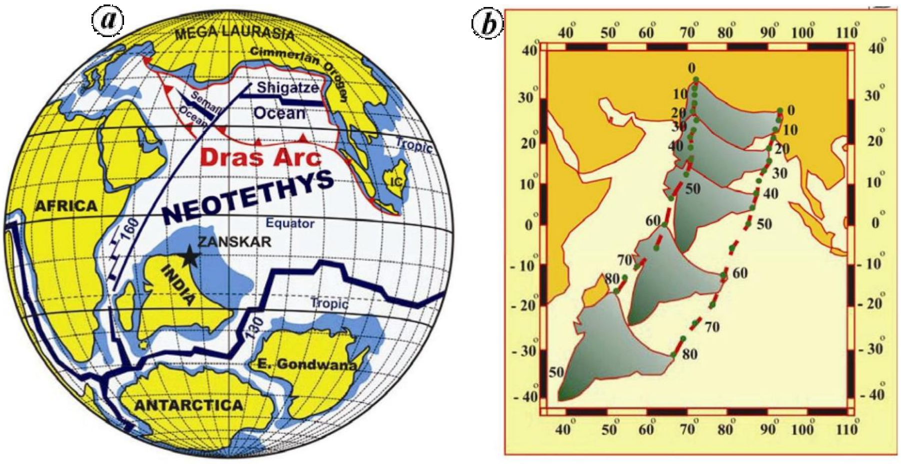

Figure 1. ***a***, Palaeogeographic reconstruction of the Neo-Tethys domain after the fragmentation of Gondwanaland and movement of the Indian plate. Of interest is the Mesozoic passive platform on the northern Indian margin, spread of the Neo-Tethys and development of the intra-oceanic Dras volcanic arc within the subduction zone. Redrawn after Stampfli and Borel[3]. ***b***, Movement of the Indian plate with reference to Asia since 80 Ma and two points in the Himalayan syntaxes. Redrawn after Copley *et al.*[4].

40.47 ± 1.3 Ma along the Shyok Suture Zone (SSZ) by integrating U–Pb zircon ages with their H_f, whole-rock Nd and Sr isotopic characters[27].

(vi) Metamorphism: The Indian continental crust was eclogitized in the vicinity of the ITSZ trench, when the ultra high pressure (UHP) coesite-bearing eclogite in Tso Morari was produced at 55 ± 7 Ma (ref. 10) or 53.3 ± 0.7 to be more precise[13,14], while these are dated at 46 ± 0.1 Ma at Kaghan in Pakistan[16,28].

(vii) Integrated geological data: Two-stage events have been recorded in southern Tibet and elsewhere indicating a ~ 55 Ma collision of an island arc system with India (Event 1) and a younger Oligocene age of the India–Asia continental collision (Event 2)[29]. Two-stage Cenozoic collision is also postulated from estimating amount of convergence: 50 Ma collision of an extended microcontinent fragment and continental Asia, and 25 Ma hard continent–continent collision[30].

In the whole gamut of evidence for the India–Asia collision, best possible age appears to be ~ 56 Ma by correlating the geochronological constraints on the deep-seated metamorphism of lithosphere with near-surface sedimentological facies and biostratigraphic age[11,12].

It is, therefore, evident that data on stratigraphy, sedimentology, palaeontology, geochronology, palaeomagnetism and palaeogeographic reconstruction provide different timings for the India–Asia collision. This article adopts a different approach to this intricate and difficult problem, and evaluates the detailed geological and geochronological data from two tectonic units, which were immediately juxtaposed across ITSZ – the plate boundary along which the two plates converged and sutured in NW Himalaya. It compares the ages of two critical units as the products of changeover from the oceanic lithospheric subduction to the continental lithospheric subduction – the Trans-Himalayan LB on the southern edge of the Asian plate and the Himalayan Tso Morari Crystallines on the northern edge of the Indian plate respectively. An attempt is made to critically answer: (i) different tectonic units that were involved in the initial India–Asia convergence, (ii) the timing of India–Asia impingement/collision and (iii) initial shaping of the Himalaya/Trans-Himalaya.

Geological framework

In the northwest, the Trans-Himalayan Mountains, the Ladakh Range and the Karakoram Mountains demarcate the northern margin of the Himalaya. Drained largely by the river Indus and its tributaries, the Shyok and Nubra rivers, these mountains constitute the most inaccessible and difficult terrain in the northwest. As the Indian plate started subducting under the Asian plate, its Neo-Tethyan oceanic floor north of the plate melted at depth to produce the intra-oceanic Shyok–Dras Volcanic arc[31–37] (Figure 1). Between this arc and the Asian plate, a thick Palaeo-Mesozoic Karakoram sedimentary sequence was deposited on the southern Asian margin[31–37]. This ocean closed along two suture zones; SSZ in the north and ITSZ towards the south. These sutures demarcate the contact between the two plates and preserve the tectonic signatures of the following geological events from the north to south respectively[31–33,35–41] (Figures 2 and 3).

(i) Initial Late Mesozoic subduction of the Neo-Tethys oceanic lithosphere along the SSZ during the Early Cretaceous–Lower Eocene with the intervening intra-oceanic Dras–Shyok volcanic island arc.

(ii) Emplacement of the younger calc-alkaline Trans-Himalayan plutons to the south of SSZ (Figure 3).

(iii) Final closure of the Neo-Tethys along ITSZ during the India–Asia collision.

Further south of ITSZ, the Himalayan Metamorphic Belt (HMB) forms the leading edge of the remobilized continental India. It was covered by the vast Tethyan Palaeo-Mesozoic Sedimentary Zone (called as the Tethyan Himalaya), deposited on the northern passive margin of the Indian plate. The deepest parts of the leading edge of the Indian plate underwent UHP metamorphism in the Tso Morari area around 55 ± 7 Ma (ref. 10) or 53.3 ± 0.7 Ma (ref. 13) at a depth of more than 100 km beneath the Trans-Himalaya. Further crustal shortening within the Himalaya witnessed the large-scale deformation, metamorphism, crustal anataxis during 45–25 Ma (see later in the article for details) and thrusting along the Main Central Thrust (MCT). This thrust brought HMB over the Proterozoic–Palaeozoic Lesser Himalayan sedimentary belt around 25 Ma which, in turn, overrode the Cenozoic Sub-Himalayan belt along the Main Boundary Thrust (MBT) about 10 Ma (Figure 4)[40–43]. The youngest phase of the southward propagating thrusting was along the Main Frontal Thrust (MFT), which juxtaposed this sedimentary belt against the alluvium of the Indo-Gangetic plains during the Himalayan collision tectonics.

A brief geological description is given below for the tectonic units which have been used in constraining the timing of the India–Asia collision.

Trans-Himalayan Ladakh batholith

Linear Trans-Himalayan batholithic belt is almost continuously developed from Astor–Deosai–Skardu region in Pakistan (Kohistan–Deosai batholith) to Kargil–Leh–Demchuk region in India (LB)[32,39]. It extends further southeast as the Kailash tonalite and the Gangdese pluton in southern Tibet[44] and LB in the Himalaya in Arunachal Pradesh (Figure 2). Regionally, the ITSZ demarcates its southern margin, while the Main Karakoram Thrust (MKT) and SSZ delimit its northern boundary in Pakistan and India[33,35,36].

This Andean-type LB is a WNW–ESE trending 600 km long and 30–80 km wide magmatic belt of the Late Cretaceous–Early Eocene age, having an exposed thickness of ~3 km (Figure 3)[39]. Petrographically and geochemically, this I-type calc-alkaline igneous complex consists of gabbro, diorite, granodiorite, tonalite and granite, though it is predominantly biotite- and hornblende granodiorite and quartz diorite[24,26,39,45]. Relatively low $^{87}Sr/^{86}Sr$ initial ratio (0.704 ± 0.0001) and high $^{143}Nd/^{144}Nd$ ratio (0.5126) indicate its magma derivation from partial melting of the north-subducting Tethyan oceanic lithospheric slab[39,46]. Smaller plutons disruptively intrude the batholith and result in distinct phases of magma mixing[23,47].

The LB contains numerous mafic volcanic enclaves and leaves large apophyses, and thus is characterized by intrusive contacts with the Dras–Shyok volcanic island arc, when it was emplaced between 100 and 40 Ma with the

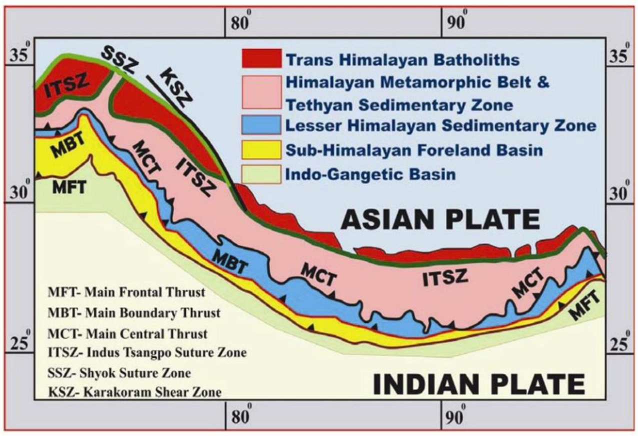

Figure 2. Geological map of the Himalaya and Trans-Himalaya showing major tectonic units of the Indian plate, its contact with the Asian plate (ITSZ and SSZ) and location of Trans-Himalayan batholith belt with reference to suture zones.

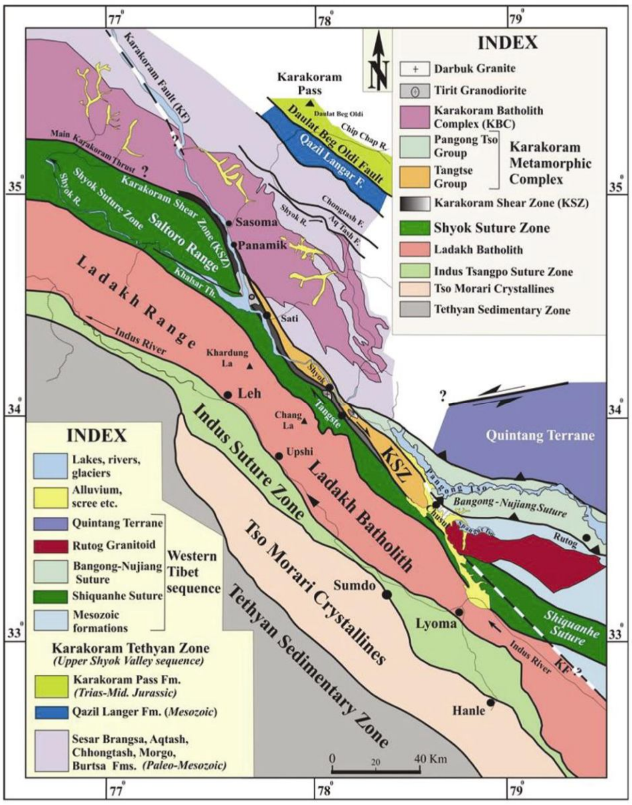

Figure 3. Geological map of the northernmost Himalaya, Trans-Himalaya and Karakoram Mountains with lithounits of the southern Asian margin, extension of the Karakoram batholith, SSZ and KSZ. Two sutures, ITSZ and SSZ contain fragmented oceanic crust pieces as ophiolites and are separated by the Trans-Himalayan Ladakh batholith. The UHP terrane in Tso Morari is juxtaposed against the southern suture. Compiled after the author's work in Ladakh and Karakoram, published literature, and Jain and Singh[36].

dominant phase ~60 Ma[24,33,39,46,48,49]. Along the Indus river north-dipping forearc and continental molassic sedimentary rocks partly cover its southern margin and are eroded material from this uplifted magmatic arc with subordinate components from the passive Indian margin sedimentary succession[21,50–53]. Locally, andesitic to rhyolite volcanics along with volcaniclastic sediments nonconformably overlie LB around Khardung near its northern margin with SSZ[23].

Although LB is largely undeformed, intensely penetrative SW-dipping ductile shear fabric characterizes its southern margin within the NW–SE trending dextral Thanglasgo Shear Zone[23]. It exhibits distinct top-to-southwest overthrust S–C ductile shear fabric, and brittle–ductile to brittle faults in the lower parts due to effects of ITSZ[42]. Deformation has caused northward tilting and simultaneous tectonic removal after its crystallization[24].

Indus Tsangpo Suture Zone (ITSZ)

Along the southern margin of LB, the ITSZ belt incorporates a complex association of tectonically imbricated volcanic arc, ophiolite belts and sediments. In the western parts around Dras and Kargil, two ophiolite belts separate an imbricated segment of the Dras volcanic association of pyroclastic and volcaniclastic sediments, and calc-alkaline tholeiitic volcanics, which are developed on the Tethyan oceanic crust as an intra-oceanic island arc[33,39,54–57]. A Callovian to Cenomanian (164–95 Ma) age has been assigned to the Dras volcanics. A volcano-sedimentary Nindam Formation sequence developed in an accretionary prism/forearc setting to the southeast of this arc[58].

Juxtaposed against the Tethyan sedimentary sequence of Zanskar in the south are the graded sandstone, siltstone and shale with large limestone exotic blocks, belonging to the Lamayuru Formation. This formation represents the north-facing continental slope deposits of the Triassic to Upper Cretaceous along the Indian passive margin[59]. Further southeast, the Nidar ophiolitic complex of ultramafics, gabbro of 139.6 ± 32.2 Ma (Sm–Nd age), basalt, shale and chert is developed on the ~170 to 125-Ma-old oceanic lithosphere[31,60–62] and represents an intra-oceanic volcanic arc.

During the closure of the Neo-Tethys, the Indus group sediments were deposited in an intermontane basin by westerly flowing palaeo-Indus River system within ITSZ and the rest unconformably over LB[21,32,50,52,53].

The overall geometry of ITSZ is southward-propagating thrusts with reverse vergence towards NE along its northern margin because of thrusting over the LB. An eroded, folded and much wider Spontang ophiolitic nappe, rooted within ITSZ, obducts southward over the Tethyan Sedimentary Zone (TSZ) in the earliest Eocene[5,18].

Tso Morari Crystallines – subducted continental lithosphere

Juxtaposed against the site of the closure of the Neo-Tethyan ocean along ITSZ, coesite-bearing UHP eclogites from the Tso Morari Complex (TMC) and Kaghan valley of Pakistan provide convincing evidence that leading edge of the northwestern part of the Indian continental lithosphere subducted to a depth of more than 100 km (Figure 4)[12–14,28,63,64].

The TMC is a ~100 × 50 km dome of NW–SE trending eclogite–gneiss complex in eastern Ladakh between TSZ and ITSZ (Figure 3). It contains: (i) highly sheared quartzo-feldspathic gneiss (Puga Formation) of probable Late Proterozoic–Cambrian age in the deepest levels, (ii) metasedimentary cover of alternating quartzite–schist, carbonaceous schist and marble (Tanglang La Formation) and (iii) the Palaeozoic intrusive granitoids (Polokongka La and Rupshu Granite)[32,65]. Numerous dark coloured, blackish-looking, small bodies of dense and heavy eclogite and retrogressed garnet amphibolite lenses are interspersed in these formations and can be spotted from a distance[42,64]. Jain and Singh[36] have provided an extensive review of TMC.

There have been various attempts to calculate the pressure and temperature of TMC on the basis of different mineral assemblages. Temperature has been estimated to range from 580 ± 60°C to 750–850°C, while pressure from 11 to 30 kbar[42,66,67]. Moreover, the presence of coesite in the Tso Morari eclogites confirms their formation

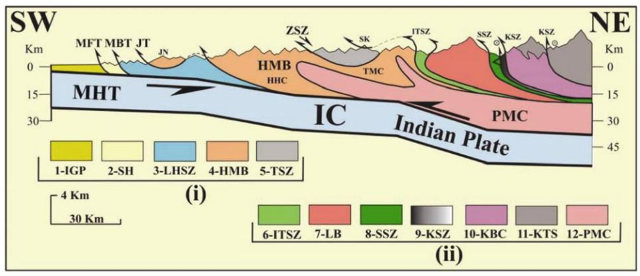

Figure 4. Geological cross-section through NW Himalaya, Trans-Himalaya and Karakoram. Himalayan collision tectonic zone: 1, Indo-Gangetic Plains (IGP); 2, Sub-Himalayan Cenozoic foreland basin (SH); 3, Lesser Himalayan Sedimentary Zone (LHSZ); 4, Himalayan Metamorphic Belt (HMB), including Lesser Himalayan Jutogh Nappe (JN), Higher Himalayan Crystalline (HHC) Belt and Tso Morari Crystallines (TMC); 5, Tethyan Sedimentary Zone (TSZ). Trans-Himalayan tectonic units: 6, Indus Tsangpo Suture Zone (ITSZ) and Spontang Klippe ophiolite (SK); 7, Ladakh batholith (LB); 8, Shyok Suture Zone (SSZ). Asian plate margin: 9, Karakoram Shear Zone; 10, Karakoram Batholith Complex (KBC); 11, Palaeo–Mesozoic Karakoram Tethyan sequence; 12, Partially molten crust (PMC); IC, Subducting Indian crust. MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MCT, Main Central Thrust; ZSZ, Zanskar Shear Zone and MHT, Main Himalayan Thrust. Note vertical exaggerate above 0 km to show topography. Partial molten mid-crust and extension of the Indian plate beneath Karakoram and further northeast are constrained from magnetotelluric, and teleseismic receiver function analysis[80–82]. Data are integrated with geology, collected during the HIMPROBE programme of DST.

at a minimum pressure of ~ 27 kbar, corresponding to a depth of nearly 90 km (refs 37 and 64). Retrograde HP eclogite-facies (20 kbar, 600°C) and amphibolite–facies metamorphism (13 kbar, 600°C) was followed by greenschist-facies metamorphism (4 kbar, 350°C) and final exhumation to the surface[10,66,68]. The *P–T* paths for the Tso Morari metapelites and eclogites are similar indicating that they followed the same tectonometamorphic history during their journey in the continental crust[66].

Northern tectonic units

Three tectonic units are developed in the immediate vicinity of the Trans-Himalayan LB: (i) SSZ as the northern suture to the Indian–Asian plates, (ii) the Karakoram Shear Zone (KSZ) and (iii) Karakoram Batholith and metamorphic complex of the southern margin of the Asian plate.

Shyok Suture Zone (SSZ): An association of dismembered ultramafics, gabbro, basalt and sediments having chert, shale and *Orbitolina*-bearing limestone define the long, linear SSZ as the northern suture during the Cretaceous[69] from NW beyond the Nanga Parbat spur to the northern part of the Kohistan–Ladakh arc as the Main Karakoram Thrust (MKT; Rolland *et al.*[33] and references therein). Early to Middle Albian foraminifers were recorded from the central part of SSZ[70]. It is exposed along the Nubra–Shyok valleys and Saltoro Range, and is thrust over the northern slopes of LB or the Shyok volcanics. It represents an initial subduction phase of the Neo-Tethyan oceanic lithosphere beneath the Asian Palaeo-Mesozoic Platform[33,36,55], and possibly extends into the Shiquanhe Suture Zone of western Tibet (Figure 3)[71].

Karakoram Shear Zone (KSZ): A very narrow zone of highly mylonitized granite-gneiss, volcanics, sediments and serpentinite intervenes SSZ and the southern Asian Plate margin along KSZ for nearly 200 km with dextral transpressional characters (Figure 3)[35]. U–Th–Pb zircon age of 68 ± 1 Ma from an undeformed calc-alkaline granodiorite and $^{40}Ar/^{39}Ar$ hornblende age of 73.6 ± 1 Ma (ref. 72), and SHRIMP U–Pb zircon age of 75.7 ± 1 Ma from the sheared mylonite[35] constrain the initial emplacement of the southern Asian margin along SSZ during 75 and 68 Ma. Younger leucogranite veins intrude KSZ and are dated 20.8 ± 0.4 Ma (ref. 35) as well as between 15.68 ± 0.52 and 13.73 ± 0.28 Ma (ref. 73), thus dextral movement along KSZ was restrained during this period.

Tectonic units of the southern Asian plate (Karakoram tectonic units)

Palaeo-Mesozoic marine sedimentary succession of southern edge of the Asian Plate passive margin is extensively deformed and metamorphosed into the Karakoram Metamorphic Complex (KMC) and is divisible in two belts (Figures 3 and 4). The southern outer Tangste group occupies vast expanse of the Pangong mountains between the Tangste gorge and Chusul in the immediate vicinity of KSZ, and is characterized by high-grade sillimanite–K-feldspar-bearing garnetiferous gneiss and schist, amphibolite, hornblende granite-gneiss and leucogranite as well as localized granulite facies metamorphics in the Pangong range[42]. Partial melting and prolific migmatization have produced the Pangong Injection Complex along the Tangste gorge with numerous dome-shaped and elongated bodies[74,75].

The inner KMC belt of the Pangong group is comprised mainly of slate, mica schist, greenschist/amphibolite and marble, calc-silicate and a band of mylonitized granite gneiss of biotite grade of middle greenschist to sillimanite–muscovite subfacies of the middle amphibolite facies[35].

Both the metamorphic belts are extensively and pervasively intruded by two distinct *I*- and *S*-type granite suites of the Karakoram Batholith Complex (KBC)[36,76,77]. These make monotonous vertical cliffs of biotite–muscovite granite in upper parts of the Nubra valley constituting the main body of KBC, and have intruded the Permo-Carboniferous Tethyan Karakoram sequence between 130 and 50 Ma and then by a younger phase between 25 and 12 Ma (refs 75, 78, 79).

Geological review of various Himalayan and Trans-Himalayan tectonic units in contact with each other clearly demonstrates that the leading northernmost continental Indian lithosphere underwent UHP metamorphism in the Tso Morari region, and was in contact with the Trans-Himalayan Shyok–Dras volcanic arc and LB throughout its geological history, and not with any Asian continental lithosphere.

Timing of the India–Asia collision

In view of prevailing controversies regarding the timing of the India–Asia collision, this work adopts a somewhat different approach for determining the initial convergence/collision timing between the Indian and the Asian plates, which are sutured and juxtaposed across ITSZ. It compares the geochronological data across ITSZ from two tectonic units, characterizing the most important geodynamic processes: (i) oceanic lithospheric subduction producing the Trans-Himalayan LB to the north, and (ii) continental lithospheric subduction causing the UHP metamorphism of TMC to the south.

Geochronology of the Trans-Himalayan LB

Pulsative crystallization and emplacement within LB occur in multiple stages at ~ 100, 72, 67, 58, 51, 41 Ma

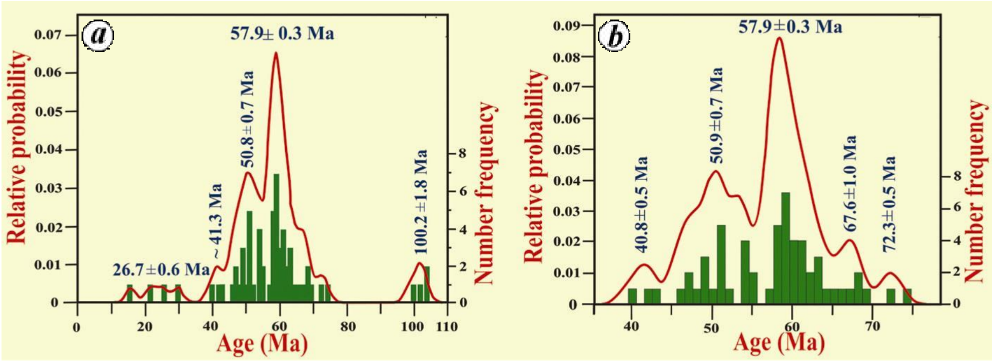

Figure 5. Published geochronological data from the Ladakh batholith. $N = 65$ till 2013. U–Pb zircon ages ($n = 62$), U–Pb allanite and monazite ($n = 1$) and Rb–Sr whole-rock isochron ages ($n = 2$). ***a***, All ages from the Ladakh batholith. ***b***, Better resolution of peaks between 35 and 75 Ma. Note peak emplacement of the Ladakh batholith at 57.9 ± 0.3 Ma with minor pulses at 72.3 ± 0.5, 67.6 ± 1.0, 50.9 ± 0.7 and 40.8 ± 0.5 Ma. Data source: ($n = 4$)[23], ($n = 2$)[24], ($n = 5$)[26], ($n = 22$)[27], ($n = 2$)[39], ($n = 5$)[46], ($n = 2$)[48], ($n = 16$)[49], ($n = 4$)[72], ($n = 3$)[77]. n = Number of samples analysed.

and younger times, possibly by melting of the earlier phases[23,24,26,39,48] (Figure 5). Weinberg and Dunlap[23] obtained SHRIMP U–Pb zircon ages of 58.1 ± 1.6 Ma from the core and relatively younger age of 49.8 ± 0.8 Ma from its rim near Leh, and interpreted these as ages of crystallization of the source igneous rock and a later magmatic phase respectively. This was followed by rapid generalized cooling and dyke intrusion at 46 ± 1 Ma. Zircon crystallization ages are 58.4 ± 1.0 and 60.1 ± 0.9 Ma from the southern and northern margins of this batholith respectively[24], while these are ~ 66 Ma in the extreme north at Hunder along the Shyok valley[26,27,49] and 68.5 ± 0.8 Ma still west[27]. Some younger components within LB date between 53.4 ± 1.8 and 45.27 ± 0.56 Ma along the southern margin[26]. Relatively low initial $^{87}Sr/^{86}Sr$ (0.704 ± 0.001) and high $^{143}Nd/^{144}Nd$ ratios (0.5126) support the derivation of its magma from partial melting of the subducting oceanic slab[39].

A detailed SHRIMP U–Pb zircon dating of central segment of LB revealed that the axis of the batholith has multiple zircon growth during 58 ± 0.8, 56.6 ± 0.9 and 54.8 ± 1.9 Ma between Khardung La and Chang La[49], followed by multiple rim growth during 62.2 and 48.8 Ma, and another phase at around 15.6 ± 1.0 Ma. The micro-granite enclaves at Chang La date almost the same as the main body. Further east, the batholith at Chumathang has zircon of 59.2 ± 0.7 Ma with rim growth at 50.4 ± 2.7, while younger intrusions date around 48.2 ± 0.8 Ma (ref. 49); the results almost match with an earlier study[48].

The southernmost part of the Kohistan–Ladakh–Palaeo-Island Arc (KLA) in immediate contact with ITSZ between Deosai and Ladakh has yielded *in situ* U–Pb zircon ages between 102.1 ± 1.2 and 50.3 ± 1.2 Ma (1σ) with a homogeneous zircon age population and average 9.4 ± 0.7 $_{\varepsilon}Hf_{(i)}$, weighted mean $_{\varepsilon}Nd_{(i)}$ of 2.6 ± 0.7 and $^{87}Sr/^{86}Sr_{(i)}$ from 0.703744 to 0.704719 (ref. 27). In contrast, post-50 Ma samples from the south are younger to 50.4 ± 1.6 Ma (youngest being 29.6 ± 0.8 in Ladakh), and yield $_{\varepsilon}Hf_{(i)}$ as low as –15, $_{\varepsilon}Nd_{(i)}$ between –9.7 and –3.6 and $^{87}Sr/^{86}Sr_{(i)}$ ranging between 0.705862 and 0.713170 (ref. 27). These ages along with a change in isotopic characters have been interpreted as a consequence of the presence of a pre-50.0 Ma intra-Tethyan oceanic arc, where a mixture of components was derived from enriched–depleted MORB mantle (E–DMM) and subducted oceanic lithosphere. The post-50 Ma samples exhibit strong isotopic variability and involvement of additional enriched components, e.g. isotopically evolved crust. A shift in isotopic composition of the KLA rocks at 50.2 ± 1.5 Ma reflects the India–KLA collision[27]. The central section of LB has samples dated between 66.0 ± 1.1 and 41.5 ± 0.5 Ma (1σ; six samples, including three from the Deosai segment). These fall within the same isotopic range for similar ages, and hence exhibit intra-oceanic character of the arc. Three samples from the northernmost segment of the arc of the LB date 68.5 ± 0.8, 25.1 ± 0.7 and 21.5 ± 0.6 Ma (1σ)[27]; the youngest ones have the most evolved isotopic composition like the Miocene granites of Karakoram due to reworking of the Asian crust. These along with many other granitoids from the northern region reflect an isotopic shift at 40 ± 1.3 Ma due to the involvement of the Mesozoic rocks of Karakoram and not the northern Indian margin[27].

Sixty-five published dates are available till 2013 from the Trans-Himalayan LB, including the Deosai segment, consisting of 62 U–Pb multi-grain and individual robust U–Pb zircon ages, one U–Pb allanite and monazite age and two Rb–Sr whole-rock isochron ages. The westernmost Kohistan segment across the western Himalayan syntaxis has not been incorporated here due its own geological history. These ages were determined by Thermal Ionization Mass Spectrometer (TIMS), SHRIMP and ICP-MS with laser ablation or multi-collector attachments (Figure 5 *a*). The relative probability curve of all the 65 ages reveals a peak of 57.9 ± 0.3 Ma from LB with minor peaks at 50.8 and 41.3 Ma (Figure 5 *a*). When extreme ages of some samples (~ 101, 15.6 to 30 Ma) are excluded and attempts are made to resolve age peaks between 35 and 75 Ma better, one obtains the oldest peak value at 72.3 ± 0.5 Ma, followed by other peaks at 67.6 ± 1.0, 50.9 ± 0.7 and 40.8 ± 0.5 Ma, besides the main peak value of 57.9 ± 0.3 Ma (Figure 5 *b*).

Geochronology of the Tso Morari Crystallines

Multi-isotopic geochronological data constrain the age of eclogite in TMC around 55 ± 7 Ma (ref. 10). This date of the UHP eclogite facies is obtained by conventional U–Pb allanite at 55 ± 17 Ma, Sm–Nd Grt–Gl–WR isochron at 55 ± 12 Ma and Lu–Hf Grt–Omp–WR at 55 ± 7 Ma. It is evident that these have large and significant errors, and do not permit precise analysis of the geologic evolution of such a young mountain belt. Subsequent exhumation reveals thermal relaxation leading to partial recrystallization under amphibolite facies at 47 ± 11 Ma (Sm–Nd Grt–Amp–WR) and 45.5 ± 4.4 Ma (Rb–Sr Ap–Ph–WR), followed by greenschist metamorphism ca. 30 Ma ($^{40}Ar/^{39}Ar$ muscovite and biotite). Last stage of exhumation is recorded from 21 ± 3 to 26 ± 3 Ma by fission-track apatite ages[10].

U–Pb SHRIMP zircon dating of the TMC pinpoints the ages of three distinct metamorphic events: (i) peak UHP metamorphism precisely at 53.1 ± 0.7 Ma, (ii) intermediate peak at 49.9 ± 0.5 Ma possibly records the HP eclogite-facies and (iii) 47.5 ± 0.5 Ma for the amphibolite-facies retrograde event (Figure 6)[13,14]. This helps us in postulating that the Indian continental lithosphere underwent the UHP metamorphism and subduction to a depth at ~ 100 km in the northwest Himalaya. The TMC was rapidly exhumed from ~ 100 km at 53.1 Ma to palaeo-depths ≤ 66 km by 49.9 Ma and ≤ 43 km by 47.5 Ma, as is documented by the SHRIMP ages, thermobarometry and isotopic closure temperatures (Figure 8)[10,42]. The exhumed UHP slices probably returned to the surface along with the buoyant continental crust broadly along the subduction zone.

Initial shaping the Himalaya/Trans-Himalaya

Various stages of the India–Asia convergence can be visualized by unfolding the present-day geological units and imaging their configuration before the closure of the Tethyan ocean. It is, therefore, pertinent to visualize the original profile of the subducting Indian lithosphere and any variation in its configuration with time. Recently procured magnetotelluric[80,81] and seismic tomography[82] profiles across the Himalaya, Trans-Himalayan and Karakoram units in the northwest clearly demonstrate that the Indian plate subducts beneath Tibet at about 5–10° or less, at present. With the current subduction angles as low as 10° at around 53 Ma, rocks must travel over 500 km along the subduction thrust to reach depths of ca. 100 km, corresponding to the UHP metamorphism. Considering the onset of the India–Asia collision approximately at 55 ± 1 Ma (ref. 11), it would have taken at least 30 Ma for the rocks to attain the UHP metamorphism with a speed of 15 km/Ma. It is, therefore, inferred that early continental and oceanic subduction in the Himalaya was at a steep angle, followed by oceanic-slab break-off[83], rapid exhumation of the UHP rocks into the crust, and resumption of continental subduction at the modern low angle[13]. Keeping this model in mind, steep oceanic and continental subduction has been proposed for the early evolution of the Himalayan and Trans-Himalayan units through the following stages.

Stage 1: Initial configuration

As mentioned earlier, Palaeo-Mesozoic sedimentary successions were deposited on the passive margins of both the Asian and Indian plates, which were separated by the Tethyan ocean where an intra-oceanic Shyok–Dras volcanic island arc evolved during 170–180 Ma (Figure 7 *a*). It is likely that calc-alkaline Karakoram batholith (~ 110–102 Ma) evolved due to partial melting of the Tethyan oceanic lithosphere during initial subduction along SSZ beneath the southern Asian plate continental margin, followed by repeated pulses till about 75–70 Ma[35,72,77]. The Tethyan ocean partially closed initially by ~ 65 Ma along SSZ.

Stage 2: Partial melting of the Tethyan oceanic lithosphere

Almost concomitantly with the suturing of the Asian plate along SSZ and its final juxtaposition along the

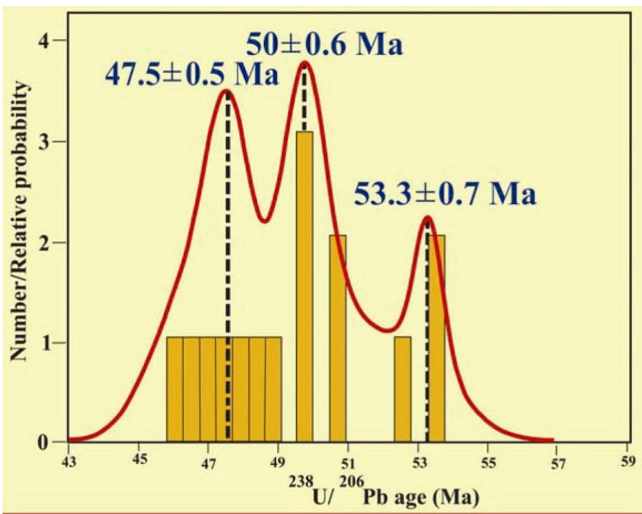

Figure 6. SHRIMP U–Pb zircon data from the Puga Group gneisses of TMC. Three distinct zircon populations grew at 53.3 ± 0.7, 50 ± 0.6 and 47.5 ± 0.5 Ma during UHP-, HP- and amphibolite facies metamorphism respectively. Redrawn from data source[13,14].

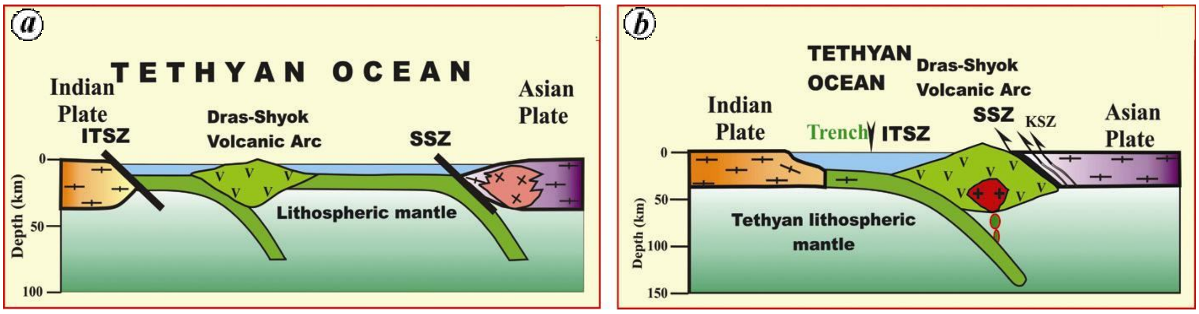

Figure 7. Initial configuration of the India–Asia convergence and southern margin of Asia. ***a***, Evolution of the intra-oceanic Shyok–Dras volcanic island arc within the Neo-Tethyan Ocean during 170–80 Ma. Development of calc-alkaline Karakoram batholith (~ 110–102 Ma) and its repeated pulses due to initial subduction of the Tethyan oceanic lithosphere along SSZ beneath the southern Asian plate continental margin. The Tethyan ocean closed initially along SSZ by ~ 65 Ma. ***b***, Subduction and partial melting of moderately-inclined Tethyan oceanic lithosphere along the ITSZ trench between 70 and 65 Ma to produce oldest calc-alkaline Trans-Himalayan Ladakh batholith between 67 and 62 Ma. Deposition of forearc pyroclastic-rich Nindam Formation during Late Cretaceous and continental slope Lamayuru Formation deposits.

northern margin of the Shyok–Dras volcanic arc, the moderately inclined Tethyan oceanic lithosphere now started subducting along the ITSZ trench mainly between 70 and 65 Ma. Partial melting of this lithosphere produced pulses of the calc-alkaline Trans-Himalayan LB between 67–62 Ma in small amounts and their intrusion into the volcanic arc rocks, possibly more along its northern margin (Figure 7 *b*). It is also likely that such melting within this domain was initiated at 105–100 Ma to explain the oldest available gabbroic–diorite rocks of Kargil[27,39,44] and nearby regions. As there was no involvement of the continental crustal component in the batholith at least in the beginning and till ~ 50 Ma (ref. 27), one can visualize the partial melting of the Tethyan oceanic lithosphere only in the evolution of LB. On the other hand, within ITSZ the forearc sequences over the southern edge of the Dras island arc produced a large amount of pyroclastic material in the Nindam Formation during Late Cretaceous[58]. Graded sandstone, siltstone and shale of the Lamayuru Formation reflected distal turbidites on the continental slope during Triassic–Jurassic with Permo-Carboniferous carbonate exotic blocks, which were possibly derived from the unstable India passive margin.

Stage 3: Emplacement of the Trans-Himalayan LB (~ 56 Ma)

Further subduction and partial melting of the Tethyan oceanic lithosphere produced bulk of the calc-alkaline Trans-Himalayan LB around 58 Ma (Figure 8 *a*). Continental crustal contamination is still not reflected within the batholith in view of its $_{\varepsilon}Hf_{(i)}$, $_{\varepsilon}Nd_{(i)}$ and $^{87}Sr/^{86}Sr_{(i)}$ ratio, thereby indicating that the continental Indian plate was not subducting beneath the Trans-Himalayan ranges during this period. These isotopic characters were only possible when the Tethyan oceanic lithosphere continuously subducted and partially melted at steeper angles, at least up to this time.

Almost instantly with peaking of the plutonic activity and growth of LB, the India continental lithosphere touched the ITSZ trench ~ 57 Ma in the south and underwent continental lithospheric subduction so as to reach the upper mantle at about 100 km and was subjected to the UHP metamorphism ~ 53 Ma (refs 13, 14). As the steep Indian continental lithosphere took some time to reach this depth for it to suffer the UHP metamorphism from near surface, difference of ~ 4–5 Ma in the two values is accounted for fast speed by which the plate underwent subduction.

Broad sedimentary facies and stratigraphic correlations postulate that minimum closure time for the Tethyan ocean within Ladakh–Zanskar was 50.5 Ma along ITSZ and the northern part of the Indian plate margin, while maximum age for the India–Asia collision was 56.5–54.9 Ma (ref. 17). The northern Indian passive margin in Zanskar was an open shelf in the newly formed foreland basin and abruptly received the volcaniclastic sandstones with serpentinite and chrome-spinel grains, suggesting the onset of orogeny[5]. The Indian continental crust reached the Trans-Himalayan trench, now marked by ITSZ, around the Palaeocene/Eocene boundary at 55.8 ± 0.2 Ma (ref. 18). Thus, metamorphic and geochronological evidence from great lithospheric depths coincides with near-surface sedimentary facies and biostratigraphic ages to constrain the onset of the India–Asia collision quite accurately at ~ 56 Ma (refs 11, 18).

Wu *et al.*[52] combined Lu–Hf isotopic characteristics and U–Pb detrital zircon ages from the oldest sediments deposited within ITSZ with the U–Pb zircon age data from the UHP metamorphic rocks of the Indian plate to conclude that the initial India–Asia collision took place at ~ 50.0 Ma.

In the support of steep subduction model, nothing conflicts with the younger episodes of the emplacement of LB between 50 and 40/25 Ma along its southern margin[27], as the remaining oceanic lithosphere may be continuously

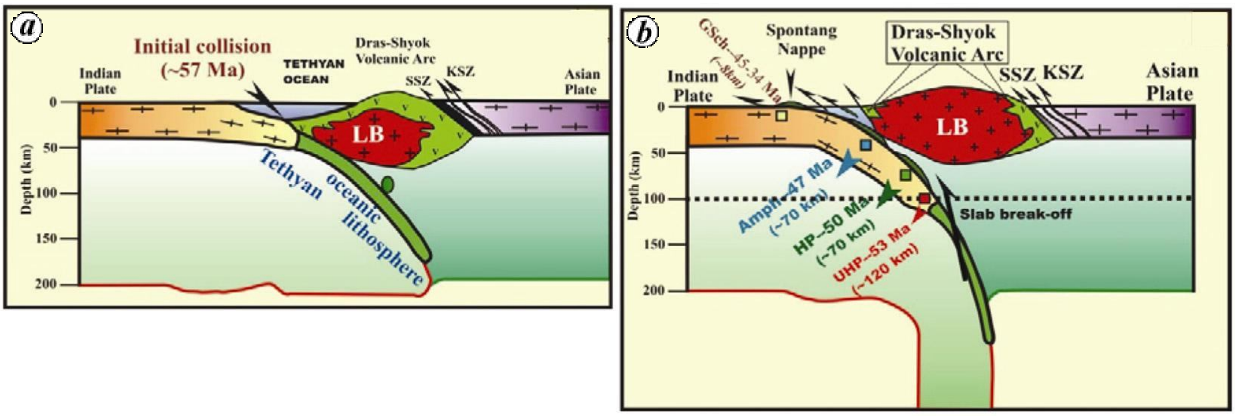

Figure 8. Partial melting of the Tethyan oceanic lithosphere, subduction of the continental Indian plate lithosphere, UHP metamorphism and exhumation. ***a***, Bulk emplacement of the calc-alkaline Trans-Himalayan Ladakh batholith (LB) around 58 Ma due to partial melting of the moderately inclined Tethyan oceanic lithosphere. Arrival of the Indian continental lithosphere at the ITSZ trench ~ 57 Ma and initiation of continental lithospheric subduction to reach ~ 100 km depth for UHP metamorphism. Gradual shrinkage in the Tethyan ocean and its minimum closure date within Ladakh–Zanskar at 50.5 Ma. ***b***, Continental lithospheric subduction of the Indian plate and development of gneiss-hosting UHP eclogites at 53.1 ± 0.7 Ma. Subsequent exhumation and cooling through various facies constrained by eclogite facies metamorphism at 49.9 ± 0.5 Ma, amphibolite facies at 47.5 ± 0.5 Ma and greenschist facies during 45 ± 2 to 34 ± 2 Ma. Exhumation rates from 1.7 to 1.2 cm/year and ca. 0.3 cm/year during this period. Only during the HP facies, the continental lithosphere melted so that the LB has $_\varepsilon Hf_{(i)}$ as low as –15, $_\varepsilon Nd_{(i)}$ between –9.7 and –3.6, and $^{87}Sr/^{86}Sr_{(i)}$ ranging between 0.705862 and 0.713170 (ref. 27).

partially melting even after the docking of India with Asia along ITSZ. Partial continental crustal contamination can also be visualized during its exhumation (see Stage 4 below), as these processes reflect the steepness of the zone of subduction.

Stage 4: UHP metamorphism and exhumation of the Indian plate

Petrological and thermobarometric studies of TMC have revealed HP mineral assemblages both in the mafic and pelitic rocks[66] as well as carbonate-bearing coesite in eclogites and coesite-bearing UHP assemblages[67], thus indicating pressure of > 39 kbar and temperature > 750°C (ref. 67). The peak metamorphism was dated 55 ± 17 Ma (U–Pb allanite), 55 ± 12 Ma by Sm–Nd (Grt–Gl–WR isochron) and 55 ± 7 Ma by Lu–Hf (Grt–Omp–WR) methods[10], thus leaving large and significant errors and not allowing precise geological evolution of the young mountain belts. SHRIMP U–Pb zircon dating of gneiss hosting UHP eclogites pinpoints the age of peak UHP metamorphism precisely in resolving the timing of continental lithospheric subduction at 53.1 ± 0.7 Ma (Figure 8 *b*)[13,14].

Subsequent exhumation and cooling paths through various metamorphic facies are constrained by dating several minerals: (i) eclogite facies metamorphism at 49.9 ± 0.5 Ma by U–Pb zircon age[14], (ii) amphibolite facies (11 kbar and 630 ± 50°C) at 47.5 ± 0.5 Ma by U–Pb zircon age[13] and 47.0 ± 11 Ma by Sm–Nd (Gr–Amp–WR), and 45.5 ± 4.4 Ma by Rb–Sr (Ap–Ph–WR) ages[10], and (iii) late-stage exhumation and stabilization in shallower crustal depths during 45 ± 2–34 ± 2 Ma by $^{40}Ar/^{39}Ar$ muscovite and biotite, and zircon fission track ages[68,83]. *P–T* path of the TMC reveals fast exhumation ca. 1.7 cm/year between 53 and 50 Ma, 1.2 cm/year between 50 and 47 Ma and subsequent decrease to ca. 0.3 cm/year (ref. 12).

Exhumation patterns of TMC clearly demonstrate that the first signatures of the Himalaya emerged from this terrain when it was exhumed from roughly 100 km depth since 53 Ma. The slab exhumed steeply along the same path as it was subducted, possibly as a consequence of a combination of (i) emplacement of ophiolites within ITSZ and lubrication caused due to serpentinization of hydrated mantle wedges along the contacts with the ITSZ[84], (ii) slab break-off[85], and (iii) extension and doming[86]. It did not melt to cause the crustal contamination of the overlying LB till it underwent exhumation during the HP metamorphism at around 50 Ma along the steep southern margin along ITSZ. Thus, sharp changes in isotopic characters within LB are explained due to steep continental subduction of the Indian lithosphere along ITSZ rather than making the India–Asia collision younger[27].

Whatever was overlying this slab also exhumed near the surface at a fast rate and was uplifted to shed detritus, not only to the Sub-Himalayan Cenozoic foreland Subathu basin in the south, but also to the ITSZ basin[62,87].

Stage 5: Metamorphism, anatexis, exhumation and erosion of HHC

Peak stage in the evolution is the core in the Great Himalaya, where the Himalayan Metamorphic Belt (HMB) was covered by the vast Palaeo-Mesozoic Tethyan Sedimentary cover, which escaped the Cenozoic metamorphism and remained largely either unmetamorphosed or was subjected to greenschist metamorphism. However, the underlying Proterozoic Indian continental lithosphere – the HMB as a northerly-dipping slab underwent peak Late Eocene, pre-MCT and Eo-Himalayan metamorphism in the upper amphibolite facies in the core of the Great Himalaya around 45 Ma (Figure 9; Hodges[40] and references therein). Regional Barrovian metamorphism was widespread at 650–700°C and 8–11 kbar and is documented by 45–35 Ma Sm–Nd syntectonic garnet and U–Pb–Th monazite from Zanskar, Garhwal and eastern Nepal[88–90]. As a part of HMB, it is likely that the Indian plate has undergone a shallower and younger continental subduction to maximum depth of 25–35 km, following a similar process associated with TMC (Jain *et al.*[91] and references therein). It was followed by cooling through 550–500°C, as has been deciphered from the $^{40}Ar/^{39}Ar$ or K–Ar hornblende and muscovite ages between 40 and 30 Ma (Sorkhabi *et al.*[92] and references therein). Ar mica cooling ages > 30 Ma from Zanskar[93], Langtang in Nepal[94], U–Pb monazite age of 36.3 ± 0.4 Ma from Annapurna[95] and 36–34 Ma Th–Pb monazite from Bhutan[96] appear to be controlled by this very Eo-Himalayan metamorphism and exhumation, and are also manifested in early erosion of the Himalayan orogen and deposition in the Cenozoic foreland basin[87].

Within this belt younger phases of Neo-Himalayan Miocene ~25 Ma metamorphism, anatexis and partial melting lead to two-stage leucogranite generation between 25 and 15 Ma, though leucosome melt production sometimes also took place during the Oligocene (33–23 Ma)[97]. These melts appear to have evolved in a southward-extruding Himalayan Channel, bounded by the coeval MCT at its base and STDZ at the top (Grujic[98] and references therein).

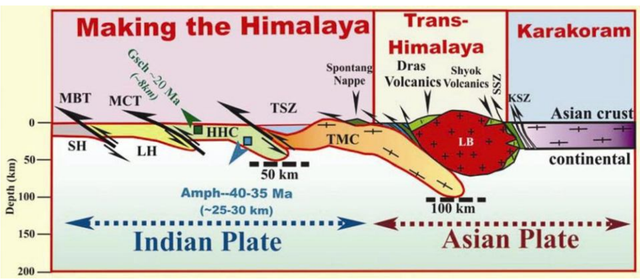

Figure 9. Metamorphism, anataxis, exhumation and thrusting. Shallower and younger continental subduction and peak Late Eocene, pre-MCT and Eo-Himalayan metamorphism in the upper amphibolite facies in core of the Great Himalaya around 45 Ma, and its subsequent exhumation, cooling and erosion. Younger Neo-Himalayan miocene ~25 Ma metamorphism, anataxis, partial melting and leucogranite generation between 25 and 15 Ma in a southward extruding Himalayan Channel along MCT and STDZ. Thrusting and imbrication along MBT and MFT during late Miocene–Pliocene–Pleistocene.

Subsequent Miocene–Pliocene–Pleistocene exhumation is widespread from different sectors of HHC, followed by its extensively erosion to produce detritus for the Siwalik group molasse within the Cenozoic foreland basin and Bengal basin[40,41,99]. Tectonically, these exhumation patterns are controlled by concomitant erosion, associated with either thrusts (MCT), extensional faults (STDZ) or windows/domes (Kishtwar Window)[99].

Conclusion

Critical evaluation of detailed geological and geochronological data from tectonic units across the suture zone between the India and Asia plates in the NW Himalaya – the ITSZ – highlights the following aspects of the 'what, when and where' the Indian plate subducted/collided with the Asian plate.

(i) The oceanic lithosphere of the Neo–Tethys ocean first started subducting beneath the intra-oceanic Dras–Shyok island arc and episodically melted to generate the Trans-Himalayan batholiths since 105 Ma in the NW Himalaya. However, bulk of the Trans-Himalayan magmatism peaked around 58 Ma.

(ii) The continental lithosphere of the Indian plate did not directly accrete with any Asian continent to make the Himalaya, initially. Hence, there was no direct continent-to-continent collision/fusion in the Himalaya in the beginning.

(iii) The continental lithosphere of the Indian plate first subducted with what then existed as a volcanic/plutonic magmatic arc to close the Tethyan ocean – the intra-oceanic Shyok–Dras volcanic island arc, intruded by the Trans-Himalayan LB, now mainly making the Ladakh range.

(iv) Timing of the first India–Asia impingement has been better constrained ~58 Ma by comparing ages and products of deep-seated and surface processes: (a) the subduction and melting of the Tethyan oceanic lithosphere – the Trans-Himalayan LB; (b) the subducted continental lithospheric and UHP metamorphosed Indian crust – the TMC and (c) biostratigraphy of the youngest marine sedimentation in Zanskar.

(v) Bulk intrusion of the Trans-Himalayan LB took place at 57.9 ± 0.3 Ma, while the UHP meatmorphism in Tso Morari was at 53.3 ± 0.7 Ma. Both the units signify the drastic geodynamic changes within ~4–5 Ma.

(vi) As the steep Indian continental lithosphere took some time to reach the depth of about ~100 km for it to have suffered UHP metamorphism from near surface, difference of ~4–5 Ma in the two values is accounted for fast speed by which the plate underwent subduction. This steep subduction also accounts for younger pulses within LB till 45 Ma without modifying the fundamental age of the India–Asia collision.

(vii) It is likely that the Himalaya first witnessed its rise and emergence from deeply exhumed terrain in the

Tso Morari, after part of the continental lithosphere had subducted and undergone UHP metamorphism ~ 53 Ma and HP metamorphism at 50 Ma.

(viii) Sequential imbrication of the Indian continental lithosphere and associated exhumation caused rise of the Himalayan mountains in a sequence form north to the south since 45 Ma.

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