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Key Points:

- Late Cretaceous subduction-related magmatic rocks with Cenozoic metamorphic ages occur in the eastern Himalaya
- The rocks formed in an intraoceanic arc setting, and accreted onto the India passive margin prior to the continental collision
- A huge and Late Cretaceous northward subduction system operated within the entire Neo-Tethys Ocean

Supporting Information:

Supporting Information may be found in the online version of this article.

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Intraoceanic Subduction System Within the Neo-Tethys: Evidence From Late Cretaceous Arc Magmatic Rocks of the Eastern Himalaya

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Abstract The tectonic evolution of the Neo-Tethys Ocean remains highly controversial, with several models existing in the community that conflict with each other. Here, we present new geochronologic and geochemical data for orthogneisses and amphibolites from the Greater Himalayan Sequence, eastern Himalayan orogen, which indicate that these rocks have Cenozoic metamorphic ages (~52–3 Ma), but were derived from Late Cretaceous (~89 Ma) magmas with arc-like and depleted mantle geochemical signatures. Considering that northern India was a passive continental margin during the Mesozoic, and the previously reported Late Cretaceous magmatic rocks in the eastern Himalaya formed in a continental rifting setting, we suggest that the studied Late Cretaceous arc-type magmatic rocks formed in an intraoceanic arc setting within the Neo-Tethys, and accreted onto the passive margin of the Indian continent prior to the terminal continental collision. When combined with the existence of Late Mesozoic and intraoceanic arc-type magmatic rocks in the western Himalaya, we suggest that a huge Late Cretaceous subduction system operated within the eastern Neo-Tethys Ocean. This study supports two subduction zones having been responsible for the consumption and closure of the Neo-Tethys basin, and a two-stage collision history between India, Asia, and the intermediate island arc system. Our data therefore provide important constraints on the evolution of the Neo-Tethys Ocean and India-Asia collisional orogeny in southern Tibet.

Plain Language Summary We have conducted petrological, geochronologic and geochemical studies of high-grade metamorphic rocks from the Greater Himalayan Sequence, eastern Himalayan orogen. Our results show that the rocks have Cenozoic metamorphic ages, but were derived from Late Cretaceous arc-type magmatic rocks. We suggest that the magmatic rocks formed in an intraoceanic arc setting within the Neo-Tethys, and accreted onto the passive margin of the Indian continent prior to the terminal continental collision, and that a huge intraoceanic subduction system operated within the eastern Neo-Tethys Ocean during the Late Cretaceous.

1. Introduction

Plate tectonic reconstructions during the past ~150 Ma are seemingly very well understood across the globe, except when dealing with the evolution and closure of the Neo-Tethys Ocean. Several competing and mutually exclusive hypotheses have emerged on this front in the past decade, which involve many plate boundary configurations having been proposed by previous workers, for example, based on paleomagnetic data (e.g., van Hinsbergen et al., 2012; Yuan et al., 2021), field relations and structural constraints (e.g., Searle, 2018) or magmatism (e.g., L. Ding et al., 2003; Rolland et al., 2023). Here, we present geochronologic and geochemical data from Late Cretaceous meta-igneous rocks exposed in the Eastern Himalayan Syntaxis (EHS), and demonstrate that they have geochemical affinity to arc-type magmatic protoliths. We show for the first time that the Late Cretaceous magmatic rocks formed in an arc setting, and represented a part of a huge subduction system that operated within the Neo-Tethys Ocean during the Late Mesozoic. They provide a new and important constraint on the subduction process and geodynamic evolution of the Neo-Tethys, and collisional orogeny between the Indian and Asian continents. All analytical methods are described in Text S1 in Supporting Information S1.

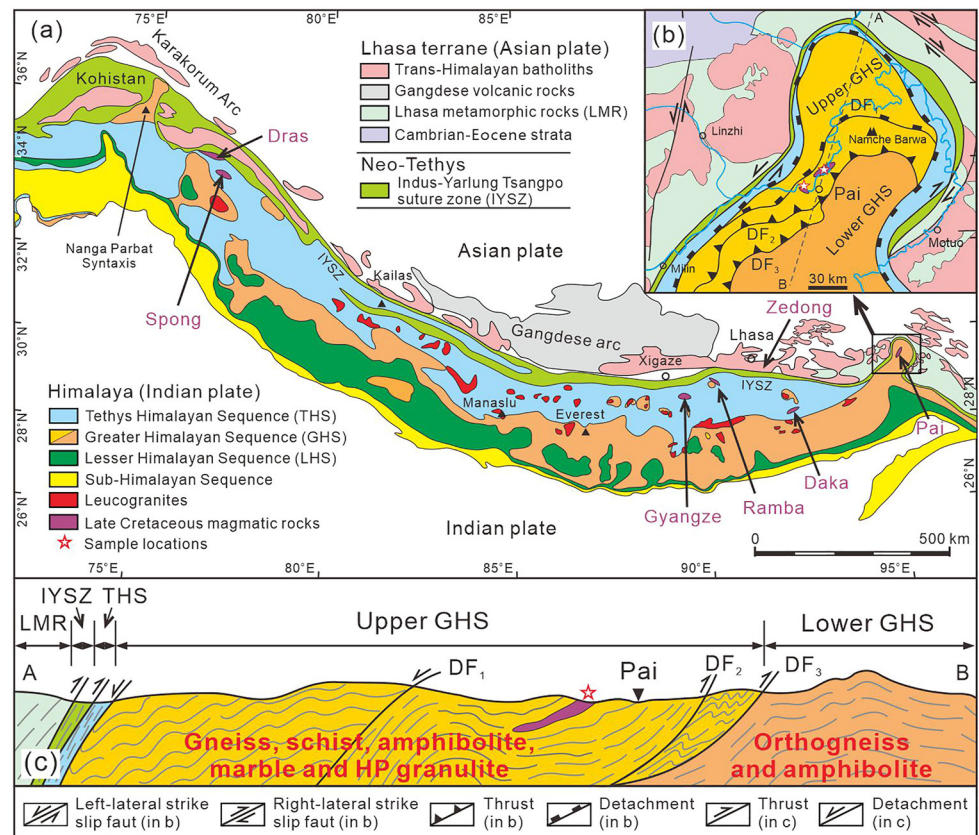


Figure 1. (a) Geological map of the Himalayan orogen showing the locations of Late Cretaceous magmatic rocks. (b, c) Geological map and cross-section of the Eastern Himalayan Syntaxis (modified after Geng et al., 2006; Xu et al., 2012). The profile location is shown in (b). DF in (b, c) refers to the ductile fault.

2. Background and Samples

The southern part of the Tibetan Plateau consists of three tectono-stratigraphic domains; from north to south, they are the Asian plate, Indus-Yarlung Tsangpo suture zone (IYSZ), and Indian plate (Figure 1a). The Asian plate is represented by the Lhasa and Karakoram terranes and the Karakoram-Ladakh-Gangdese magmatic arc within the terranes. The IYSZ comprises remnants of oceanic crust from the Neo-Tethys—a huge oceanic basin that separated Asia and India during the Late Paleozoic to Mesozoic. The Indian plate is represented by the Himalayan orogen, which consists of three main lithotectonic units: the Lesser, Greater, and Tethyan Himalayan Sequences (LHS, GHS, and THS, respectively; Figure 1). The LHS, GHS, and THS mainly consist of Proterozoic, Late Proterozoic to Paleozoic, and Late Proterozoic to Mesozoic metasedimentary rocks, respectively (Yin & Harrison, 2000).

The GHS in the EHS includes the upper and lower GHS units that are separated by a ductile shear zone or thrust fault (DF₃; Figures 1b and 1c; Xu et al., 2012). The upper (northern) unit occurs as a NE-SW striking belt within the northwestern part of the GHS and includes three tectonic slices that are separated by ductile shear zones or detachment and thrust faults (DF₁ and DF₂; Figures 1b and 1c). The upper GHS unit consists of gneiss, schist, amphibolite, marble, calc-silicate rock and high-pressure (HP) granulite and experienced an extended period of upper amphibolite-facies to granulite-facies metamorphism and partial melting from ~50 to ~3 Ma (Booth et al., 2004, 2009; L. Ding et al., 2001; Peng et al., 2018, 2022; Tian et al., 2016, 2020; Z. M. Zhang et al., 2012, 2015; Z. M. Zhang, Ding, Palin, et al., 2022). The lower (southern) GHS unit is composed mainly of migmatitic amphibolite and orthogneiss and underwent upper amphibolite-facies metamorphic and partial melting. Late Paleoproterozoic, Neoproterozoic, Early Paleozoic, and Early and Late Cretaceous protolith ages have been obtained from the orthogneisses and amphibolites of the GHS (Booth et al., 2004, 2009; Guo et al., 2008; Peng et al., 2018; Z. M. Zhang et al., 2008, 2012; Z. M. Zhang, Ding, Palin, et al., 2022).

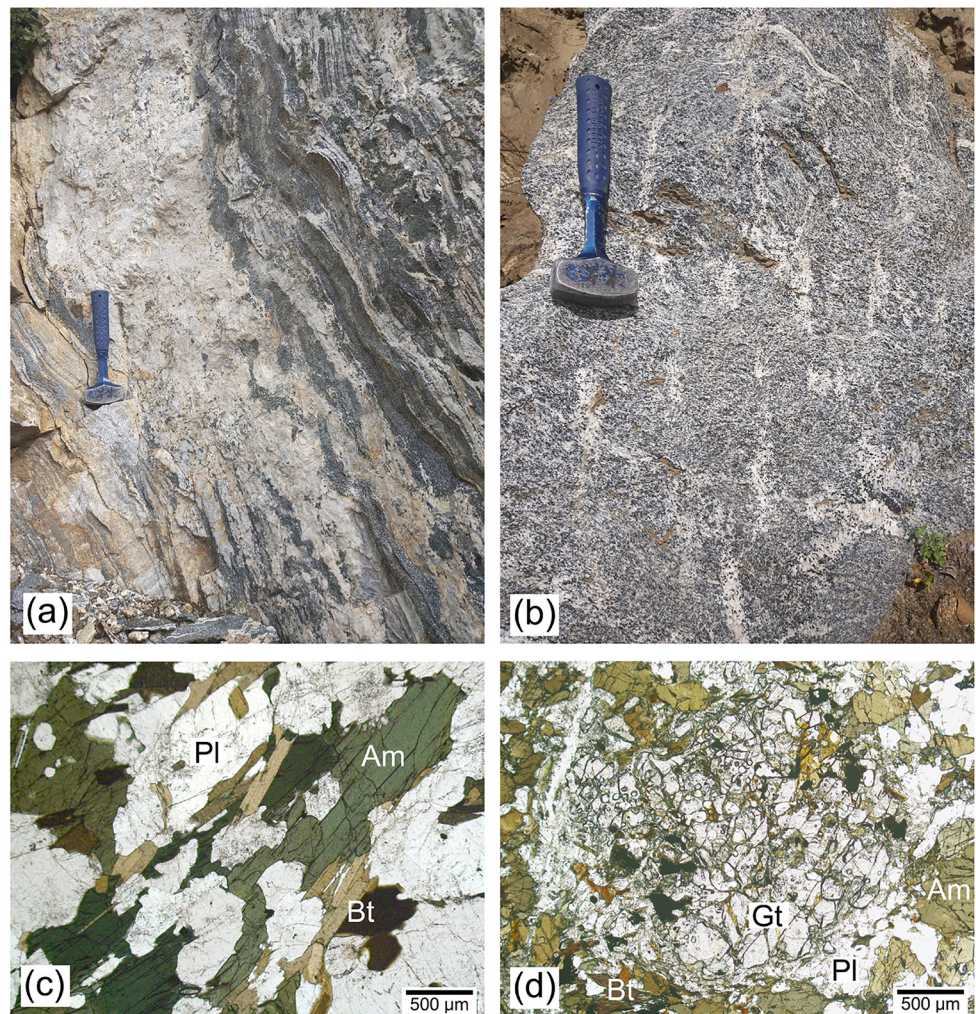


Figure 2. (a, b) Field photographs of amphibolites. The migmatitic amphibolite (dark gray) contains abundant felsic leucosome bands and veins (white; a), and patchy felsic leucosomes (white; b). The hammer in (a) and (b) for scale is 35 cm long. (c) Photomicrograph of gneiss containing amphibole, plagioclase, biotite, and quartz. (d) Photomicrograph of garnet amphibolite containing garnet, amphibole, biotite, plagioclase, quartz, and ilmenite. The garnet grain is replaced by fine-grained amphibole, biotite and plagioclase along its margin. Mineral abbreviations in (c) and (d): Am-amphibole, Bt-biotite, Gt-garnet, and Pl-plagioclase.

Based on previous detailed analyses of structural elements and fabrics (Xu et al., 2012) and our new field and microscopic observations, we suggest that the GHS in the EHS experienced four stages of deformation during the Cenozoic continental collision. The first stage of deformation (D1) was characterized by the formation of prominent foliation in HP granulites during prograde metamorphism and partial melting related to subduction of the Indian continental crust. The foliation is defined by the alignment of oval garnet, prismatic kyanite, feldspar and quartz bands and ribbons, and biotite flakes in pelitic and felsic HP granulites, and leucosome bands parallel to the main foliation of pelitic, felsic and mafic HP granulites (Figure 2a). The second stage of deformation (D2) involved the formation of ductile shear zones DF₁, DF₂, and DF₃, which constitute the boundaries of tectonic slices within the GHS (Figures 1b and 1c; Xu et al., 2012). DF₁ is a ductile detachment zone with foliation dipping gently to the NW with a NW-SE or WNW-ESE trending stretching lineation, and a top-to-NW or WNW shear sense. Both DF₂ and DF₃ are thrust-related ductile shear zones with a transverse stretching lineation in the foliation that dips moderately to the N or NW. These shear zones developed mylonites with kinematic indicators displaying a top-to-ESE or S shear sense, indicating that the upper GHS unit was thrust above the lower GHS unit (Figure 1c). The third stage of deformation (D3) is marked by refolding of DF₁ and formation of tight upright folds with nearly NW-SE trending axial planes, sub-vertical flow cleavage in incompetent rocks and fracture

cleavage in competent rocks (Xu et al., 2012). These structures were formed by regional nearly N-S shortening in the middle and upper crust during the second stage of exhumation of the GHS. The fourth stage of deformation (D4) formed gentle folds with nearly NS-oriented axial planes and refolded fold hinges, reflecting nearly E-W shortening in the shallow crust during the late exhumation of GHS (Xu et al., 2012). It is noted that no pre-collisional deformation has been identified from the GHS in the EHS.

The studied gneisses (orthogneisses or dioritic gneisses) and amphibolites occur as thick layers or lenses within the upper GHS unit in the Pai area (Figures 1b and 1c) and show a gneissic and banded structure, with abundant layers and patches of felsic leucosomes (Figures 2a and 2b). These rocks consist of plagioclase, amphibole, biotite and quartz, with or without garnet (Figures 2c and 2d), indicating peak metamorphism of upper amphibolite- and granulite-facies conditions. The garnet is replaced along its margins by a symplectitic corona consisting of fine-grained amphibole, biotite, and plagioclase (Figure 2d), which is a typical texture formed during the exhumation of HP mafic granulites (Z. M. Zhang, Ding, Palin, et al., 2022). The studied rocks have the same deformation foliation, and metamorphic and migmatitic structure as the associated gneisses, schists and HP granulites of the upper GHS unit, indicating that all of the rocks experienced coherent Cenozoic deformation, metamorphism and anatexis during the subduction and exhumation of Indian continental crust.

3. Results

Zircon grains from eight gneiss samples mostly have stubby prismatic shapes and core-rim textures. Core domains exhibit wide-banded or oscillatory zoning patterns, whereas rims have patchy zoning or no zoning in cathodoluminescence images (Figure 3). A few zircon grains without core-rim textures show rounded forms and patchy zoning (Figure 3h). One hundred and twenty spot analyses performed on zircon core domains yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 80.8–99.4 Ma (Table S1; Figure 4), with an age peak of ~89 Ma (Figure 5), and high Th/U values ranging from 0.210 to 1.276 (Table S1). The zircon cores show fractionated rare earth element (REE) patterns, with the depletion of light rare earth element (LREE) and enrichment of heavy rare earth element (HREE), and significant negative Eu anomalies (Figure 6), indicating that the zircon core domains are typical of magmatic zircons. Therefore, we interpret the ages of ~89 Ma to represent the crystallization age of the gneiss protoliths.

Fifteen spots from zircon rim domains and zircon grains without a core-rim structure yielded $^{206}\text{Pb}/^{238}\text{U}$ ages of 51.8–3.0 Ma (Table S1; Figure 5). These spots recorded low Th/U ratios of 0.005–0.181, low REE contents, and fractionated REE patterns (Figure 6), indicating that the analyzed domains had a metamorphic origin, and the obtained ages of 51.8–3.0 Ma represent the metamorphic timing of the gneisses.

Lu-Hf isotopic analyses of magmatic zircon domains from seven gneisses show that these domains have similar and low $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of 0.00028–0.00130, and initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.28303 to 0.28313. These zircon grains therefore have high $\epsilon_{\text{Hf}}(t)$ values of +10.9 to +14.7, and young two-stage Hf model ages ranging from 214 to 457 Ma (Table S2).

The studied rocks have SiO_2 of 46.87–60.42 wt.%, Al_2O_3 of 14.42–18.63 wt.%, MgO of 3.27–8.39 wt.%, CaO of 5.49–8.66 wt.%, Na_2O of 3.19–3.89 wt.%, K_2O of 1.12–2.57 wt.%, and A/CNK of 0.62–0.89 (Table S3). They are therefore metaluminous and calc-alkalic and petrologically classified as metamorphosed gabbro or diorite. The rocks show fractionated whole-rock REE patterns with LREE enrichment and HREE depletion, mostly with slight negative Eu anomalies (Figure 7a), enrichment of large ionic lithophilic element (LILE), and significant negative Nb, Ta, and Ti anomalies (Figure 7b). These geochemical features are diagnostic of magmas produced in subduction zones.

4. Discussion

4.1. Origin of the Late Cretaceous Magmatic Rocks From the Himalayan Orogen

Cenozoic high-grade metamorphic rocks and associated granites form the core of the Himalayan orogen, which resulted from the Early Cenozoic collision between India and Asia (Kohn, 2014; Searle et al., 2011; Yin & Harrison, 2000). Nonetheless, pre-Cenozoic magmatic rocks and their metamorphosed equivalents are common in the Himalayan orogen and can provide key constraints on the formation and evolution of the northern margin of Indian continent, and Paleo- and Neo-Tethyan Oceans (Chen et al., 2018; Hu et al., 2010; Kapp & DeCelles, 2019; Z. M. Zhang et al., 2012; Zhu et al., 2009).

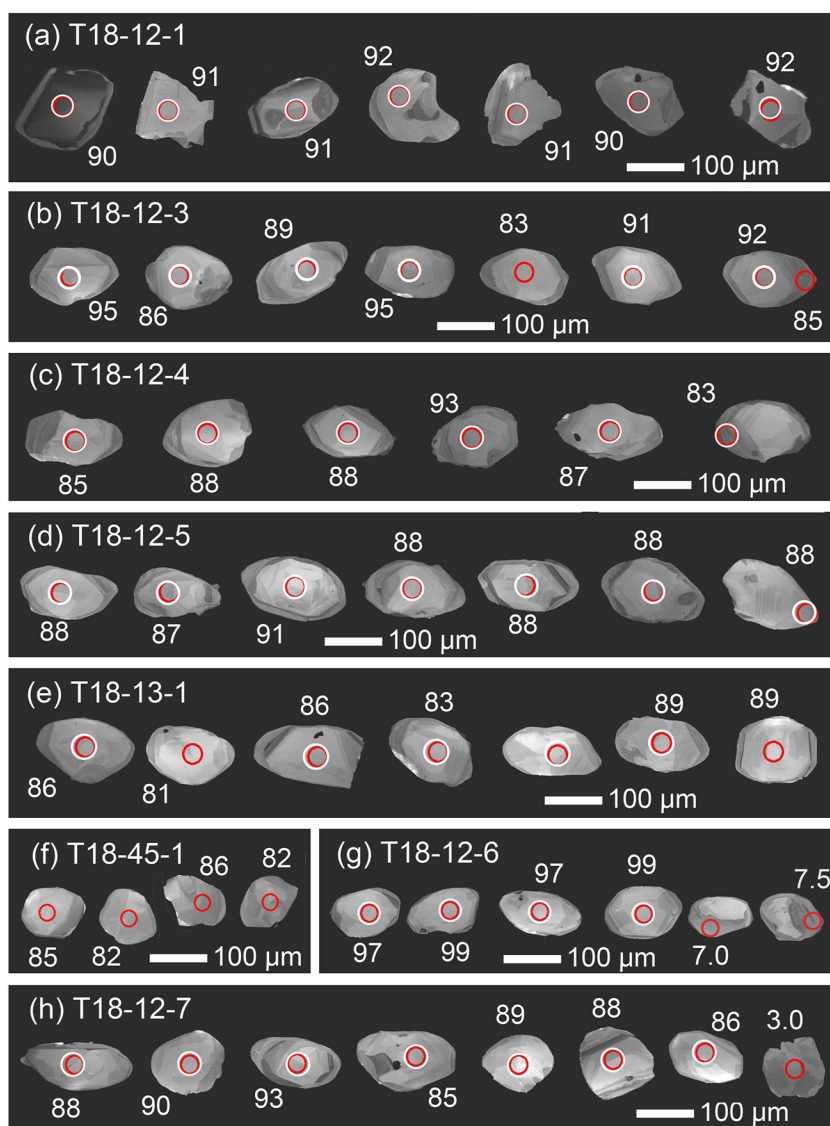


Figure 3. Cathodoluminescence images of representative zircon grains of the Pai gneisses. White and red circles refer to locations of U-Pb dating and Hf isotope analyses, respectively, and relevant U-Pb ages (in Ma) are marked near the circles.

In the Himalayan orogen, Early Cretaceous bimodal magmatic rocks occur in a pseudo-linear belt that extends for >1,500 km within the THS, and were interpreted to form in the continental rifting-related extensional environment (Chen et al., 2018; Hu et al., 2010, 2016; Huang et al., 2019). In the eastern Himalaya, Late Cretaceous magmatic rocks have been documented from the Daka, Ramba, and Gyangze areas (Figure 1a). The Daka Late Cretaceous (~92 Ma) pillow basalts in the THS show geochemical affinity to oceanic island basalt, and were related to the initial breakup of the Tethyan Himalaya and Indian terranes (Huang et al., 2018). The Ramba Early Cretaceous gneisses and Late Cretaceous (~92 Ma) amphibolite occur within metasedimentary rocks in the THS and show depleted mantle-like isotopic compositions (Z. C. Liu et al., 2014). The Gyangze Cretaceous (~121–90 Ma) diabase bodies in the THS display geochemical characteristics of mid-oceanic ridge basalt, and represent mantle partial melts that formed in extensional regimes during the breakup of East Gondwana (C. Wang, Ding, Liu, et al., 2016; Y. Y. Wang, Gao, et al., 2016). These studies indicate that the northern margin of India experienced continental rifting during the Late Mesozoic as opposed to arc magmatism. Moreover, other evidence, such as sedimentation of the THS, also supports the northern margin of Indian continent having been a passive margin rather than an active margin during the Late Paleozoic to Mesozoic (Garzanti & Hu, 2015; Green et al., 2008; Hu et al., 2016; Searle, 2018).

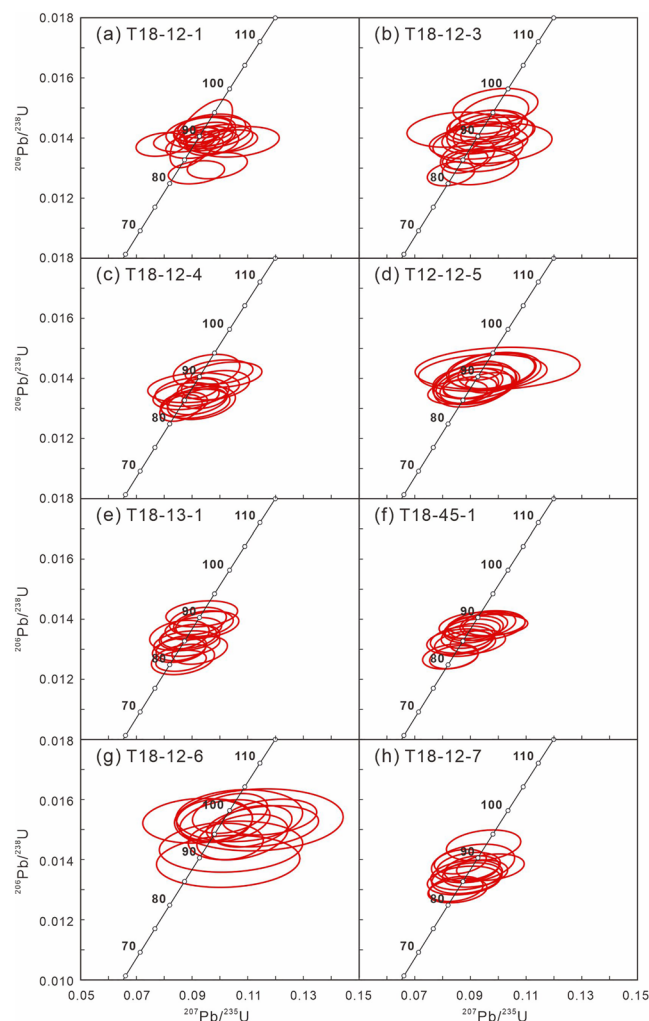


Figure 4. U-Pb concordia diagrams of zircon magmatic cores from the Pai gneisses.

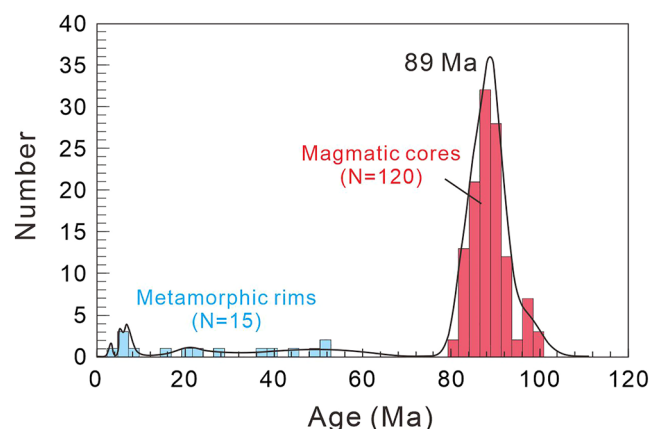


Figure 5. Relative probability diagram of zircon U-Pb ages from the Pai gneisses.

In the western Himalaya, Late Cretaceous magmatic rocks from the Dras and Spong areas occur alongside or within the northern margin of the THS (Figure 1a). The Dras mafic volcanics and gabbros are classified as sub-alkaline tholeiites and show enrichment in LILE and LREE but depletion in HFS (e.g., Nb, P, Zr, and Ti), which are geochemical features of arc-type magmatic rocks (Bhat et al., 2019). In addition, the subduction-related felsic volcanic rocks in the Dras area have Late Jurassic (~156–160 Ma) zircon ages, indicating that subduction initiated during the Late Jurassic (Walsh et al., 2021). The Spong arc contains gabbros, basalts, andesites, and volcano-sedimentary rocks, alongside Late Cretaceous (~88 Ma) andesitic lavas, all of which were emplaced onto the older oceanic basement of the Spong-tang ophiolite within the THS (Bhat et al., 2019; Pedersen et al., 2001; Walsh et al., 2019, 2021). Both the gabbros and basalts have geochemical affinity to MORB-type and arc-related mafic rocks, and the gabbros yield zircon U-Pb ages of 133–136 Ma with initial $\epsilon_{\text{Hf}}(t)$ values of +14 to +16, indicating formation from Early Cretaceous depleted mantle sources (Buckman et al., 2018). Many studies have proposed that the Dras and Spong arcs formed in an intra-oceanic island arc setting within the Neo-Tethys Ocean and accreted onto the northern Indian margin before the onset of India-Eurasia continent-continent collision (Figure 8; Buckman et al., 2018; Corfield et al., 2001; Pedersen et al., 2001; Searle et al., 1997; Walsh et al., 2019, 2021).

In the EHS, Peng et al. (2018) revealed that the upper GHS garnet amphibolites in the Pai area were derived from Late Cretaceous (~91 and ~86 Ma) mafic magmatic rocks. They proposed that the magmatism is similar to the Late Cretaceous mafic dykes within the THS, and probably related to tectonic events on the northern Indian passive margin before its collision with the Eurasian Plate. The garnet amphibolites contain plagioclase, amphibole, biotite, quartz and magnetite, and abundant felsic leucosome bands that occur parallel to the foliation of hosting rocks. Petrological and geochronological studies show that the garnet amphibolites experienced Late Miocene (~11.4–8.2 Ma) upper amphibolite- to HP granulite-facies peak metamorphism under conditions of 670–750°C and 8.5–10.5 kbar, and subsequently overprinted lower amphibolite-facies retrograde metamorphism under conditions of 600–700°C and 6.2–3.1 kbar, recording a clockwise metamorphic *P-T* path (Peng et al., 2018).

Our study shows that the late Early Eocene to Pliocene (~51.8–3.0 Ma) dioritic gneisses in the Pai area were derived from Late Cretaceous (~89 Ma) intermediate magmatic rocks. Moreover, the studied meta-magmatic rocks are metaluminous and calc-alkalic, and characterized by fractionated REE patterns, enrichment of LILE, and have negative Nb, Ta, and Ti anomalies (Figure 7). Inherited magmatic zircons in the orthogneisses have depleted mantle-like Hf isotopic compositions. These indicate that the Late Cretaceous magmatic rocks have arc-like geochemical signatures, and were derived from partial melting of a depleted mantle wedge above a subduction zone.

Based on the northern Indian continent forming as a passive margin during the Late Paleozoic and Mesozoic, we suggest that the Late Cretaceous arc-type magmatic rocks from the eastern Himalayan orogen formed in an intraoceanic arc setting within the Neo-Tethys (Figure 8). These rocks have probably accreted onto the passive margin of India prior to the terminal continental collision as they witnessed the same Cenozoic metamorphic, anatexis and deformation processes as the upper GHS rocks. As described above, previous studies demonstrated that the upper GHS rocks in the EHS underwent

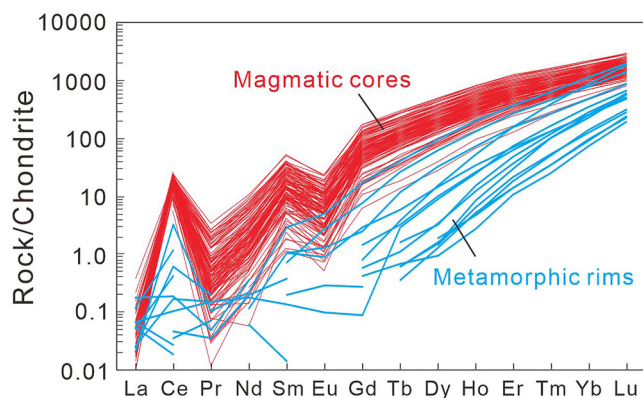


Figure 6. Chondrite-normalized rare earth element patterns of zircon from the Pai gneisses.

amphibolite-facies to HP granulite-facies metamorphism and partial melting during the Cenozoic (~50–3 Ma).

4.2. Large-Scale Intraoceanic Subduction System Across the Neo-Tethys

It is widely accepted that a long-lived Neo-Tethyan subduction zone operated along the southern margin of Asia during the Late Triassic to Early Paleocene, as a Mesozoic continental magmatic arc is well documented from the southern part of Lhasa and Karakoram terranes (Chapman et al., 2018; Coulon et al., 1986; Debon et al., 1986; Ravikant et al., 2009; Searle & Hacker, 2018; C. Wang, Ding, Zhang, et al., 2016; Yin & Harrison, 2000). The remnants of this magmatic arc extend for over 2,500 km from the Karakoram, through Ladakh to Gangdese (Figure 1a), and consist of the Trans-Himalayan batholith, which contains voluminous hornblende and biotite-bearing granites, granodiorites, and diorites of calc-alkaline I-type affinity (Chung et al., 2005, 2009; L. Ding et al., 2003; Harris et al., 1988; Mo

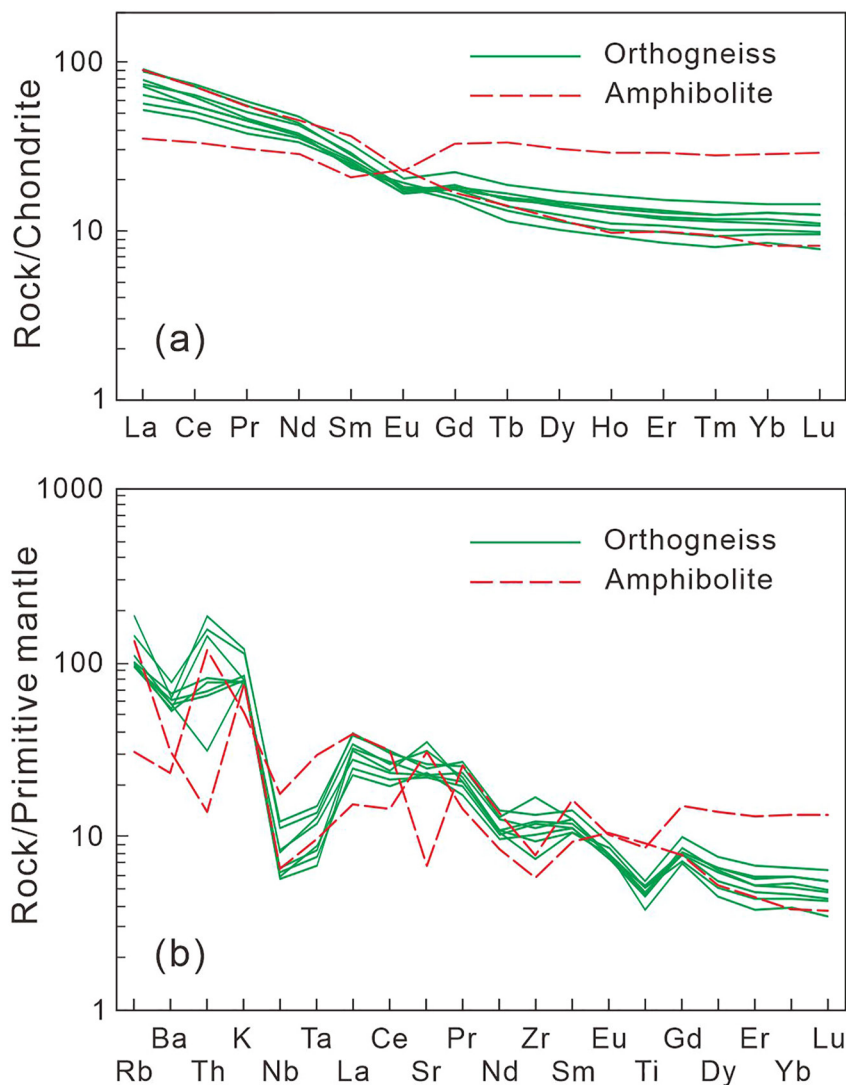


Figure 7. (a) Chondrite-normalized rare earth element patterns, and (b) primitive mantle-normalized trace element patterns of the Pai gneisses and amphibolites.



Figure 8. Plate tectonic reconstruction of the Neo-Tethys Ocean during the Late Cretaceous. Red lines with triangles indicate subduction zones and their subduction directions, and purple and gray lines indicate spreading ridges and transform boundaries, respectively. Modified after Chatterjee et al. (2013) and Hall (2012).

et al., 2005, 2007, 2008; Rolland, 2002; C. Wang, Ding, Zhang, et al., 2016; Wen et al., 2008; Zhu et al., 2011, 2019, 2023). This batholith and associated volcanic rocks mostly were generated during the Mesozoic to Early Paleocene, and therefore provides undisputed evidence for prolonged northwards subduction of Neo-Tethyan oceanic lithosphere beneath the southern margin of the Asian plate (Chu et al., 2006; L. Ding et al., 2003; Guo et al., 2011; Ji et al., 2009; Wu et al., 2014; Yin & Harrison, 2000; Z. M. Zhang, Ding, Dong, et al., 2022; Zhu et al., 2011, 2019).

In the western Himalaya, based on the existence of Kohistan, Dras and Spong island arcs, one or two intraoceanic subduction zones within the Neo-Tethys were proposed in addition to the subduction zone along the southern Asian margin. Rolland (2002), Chatterjee and Scotese (2010) and Chatterjee et al. (2013) considered that a Late Cretaceous northwards subduction zone within the Neo-Tethys resulted in the formation of Kohistan-Dras (or Kohistan-Ladakh) island arc. Recently, Buckman et al. (2018) and Walsh et al. (2019, 2021) also argued that a northwards intraoceanic subduction zone was present within the Neo-Tethys, which is related to the formation of the Dras-Spong-Zedong island arc during the Late Cretaceous. By contrast, Corfield et al. (2001) and Searle (2018) suggested that two NNE-dipping subduction zones operated within the western part of eastern Neo-Tethys during the Late Cretaceous: one to the south beneath the Late Cretaceous Spong arc, and one to the north beneath the Late Cretaceous-Paleogene Kohistan island arc (Figure 8).

Currently, most studies suggest that only one intraoceanic subduction zone operated within the eastern Neo-Tethys; however, it is difficult to establish whether any more were active during the Late Cretaceous, as key evidence

from the rock record (i.e., Late Mesozoic arc-type magmatic rocks) is either controversial or missing in the eastern Himalaya. In previous studies, Late Jurassic (155–160 Ma) arc-type magmatic rocks from the Zedong area in the eastern Gangdese arc have been interpreted to form in an intraoceanic arc setting, and were named the Zedong arc or intraoceanic Zedong terrane (Aitchison et al., 2000; Buckman et al., 2018; W. Liu et al., 2020; McDermid et al., 2002; Walsh et al., 2019, 2021). Thus, the Zedong arc may represent the eastward extension of the Kohistan-Dras or Dras-Spong island arc in the western Himalaya. However, L. L. Zhang et al. (2014) argued that the Zedong arc represents a slice of the active continental margin developed on the southern margin of the Lhasa terrane as a result of the northward subduction of the Neo-Tethys Ocean during the Late Jurassic, rather than the vestige of an intraoceanic arc. In addition, Kapp and DeCelles (2019) proposed that southward rollback of the subducted Neo-Tethys oceanic slab during the early Middle Jurassic may have led to rifting of the Zedong arc from the Lhasa terrane margin, and the Zedong arc may have accreted back to the Asian margin during the Late Jurassic.

Our study shows for the first time that Late Cretaceous arc-type magmatic rocks, which we refer to as the Pai arc, occur in the upper GHS unit of the EHS, and moreover probably formed in an intraoceanic arc setting. This finding provides favorable evidence for a Late Mesozoic intraoceanic arc that operated within the eastern segment of eastern Neo-Tethys. The Pai arc in the eastern Himalaya and the Spong and Dras arcs in the western Himalaya thus formed a large-scale intraoceanic subduction zone extending over 2,000 km (Figure 8).

Most studies have proposed that the Dras and Spong arcs were related to northward subduction of the Neo-Tethys (Buckman et al., 2018; Chatterjee & Scotese, 2010; Chatterjee et al., 2013; Corfield et al., 2001; Jagoutz et al., 2015; Rolland et al., 2000, 2002; Searle, 2018; Walsh et al., 2019, 2021). By contrast, some studies argued that a south-directed subduction system existed within the Neo-Tethys during the Late Mesozoic (Hall, 2012; Hässig et al., 2015; Rolland, 2017). Hall (2012) suggested that southwards-directed subduction of the Neo-Tethys initiated at ~160 Ma along the northeastern margin of East Gondwana. This resulted in the formation of a continental or intraoceanic arc (Woyla arc) at the continental margin or within the Neo-Tethys north of Australia and India, and the separation of continental fragments from East Gondwana. Following the Borneo block colliding with the Sundaland margin, the subduction polarity reversed from south- to north-directed at the Woyla Arc. Andjić et al. (2022) argued that a single Dras-Kohistan-Ladakh arc formed above a south-dipping intraoceanic

subduction zone and accreted to Eurasia during the Early Cretaceous, after which it evolved above a north-dipping subduction zone. Based on global tectonic reconstructions and seismic tomography, Yan et al. (2023) reported that a south-dipping intraoceanic subduction system within the Neo-Tethys allowed reasonable geological reconstructions during the Jurassic-Cretaceous period.

Because the Pai arc is geologically dissimilar to the eastern Gangdese arc, which contains evidence for multiple episodes of Mesozoic magmatism and metamorphism between the Late Cretaceous and Paleocene (H. X. Ding et al., 2022; Palin et al., 2014, 2015; L. L. Zhang et al., 2010; Z. M. Zhang, Ding, Dong, et al., 2022), we speculate that the Pai arc may have been emplaced southwards onto the northern India passive margin prior to the closure of the Neo-Tethys, and therefore the Pai arc generated above a north-dipping intraoceanic subduction zone during the Late Cretaceous (Figure 8). Consequently, we suggest that a huge intraoceanic subduction system existed across the eastern Neo-Tethys Ocean, had a northwards-directed subduction polarity, and was sustained until at least the Late Cretaceous.

4.3. Implications for Evolution of the Neo-Tethys and India-Asia Collision

Although many independent lines of geological evidence show that the Neo-Tethys was a prominent ocean separating the Asian continent (Lhasa terrane) from the Indian continent throughout the Mesozoic (Figure 8), its destruction and final closure have been the subject of intense debate. Some studies proposed that the whole Neo-Tethyan basin was almost entirely consumed by a single, long-lived subduction zone along its northern margin (Stampfli & Borel, 2002; Wu et al., 2014). By contrast, most studies argued that the Neo-Tethys Oceanic slab was consumed by two subduction systems (Aitchison et al., 2000, 2007; Chatterjee et al., 2013; Clift et al., 2014; Corfield et al., 2001; Gibbons et al., 2015; Hébert et al., 2012; Searle, 2018; Searle et al., 1988; Van der Voo et al., 1999). For example, Jagoutz et al. (2015) suggested the existence of two, almost parallel, northward dipping subduction zones between the Indian and Eurasian plates during the Cretaceous period, with the combined pull of two subducting slabs generating the anomalously rapid convergence between India and Eurasia. While this previous result was based on paleomagnetic and limited geochemical data, our results provide new field-based petrological and geochemical evidence for two north-dipping subduction zones operating independently along the southern Asian margin and within the Neo-Tethys during the Late Cretaceous, which together led to the consumption and closure of the Neo-Tethys Ocean (Figure 8).

When, how, and where the initial collision occurred between the Indian and Asian plates remain highly controversial (Aitchison et al., 2000, 2007; Garzanti & Hu, 2015; Green et al., 2008; Hu et al., 2016; Kapp & DeCelles, 2019; van Hinsbergen et al., 2012). Our result supports arguments for the India-Asia collision having experienced dual collision, with an initial collision between the northern India margin and the Late Cretaceous intraoceanic arc, and a final collision between the Indian craton and combined intraoceanic arc terrane and Asian continent (e.g., Chatterjee et al., 2013; Gibbons et al., 2015; Searle, 2018), rather than an early collision between the Gangdese continental arc and intraoceanic arc, and a late collision between the magmatic arc and Indian continent (Andjić et al., 2022; Corfield et al., 2001; Rolland, 2002). Moreover, our result suggests that India collided with the intraoceanic arc during the latest Cretaceous to Paleocene, while the collision of India + intraoceanic arc with Asia initiated at least by the Early Eocene in the eastern Himalaya. This is constrained due to the GHS in the EHS, including the Late Cretaceous (~89 Ma) magmatic rocks within the upper GHS unit, having undergone coeval and coherent metamorphism starting from the late Early Eocene (~52 Ma), which gives a minimum age of India-Asia collision. This result is clearly distinct from the previous proposals that the India-intraoceanic arc collision occurred at ~60–52 Ma and that the final India-Asia collision occurred as late as ~35 Ma (Aitchison et al., 2007; Gibbons et al., 2015).

Further studies are needed to find more Late Mesozoic arc-type rocks in the eastern Himalaya, reveal the structural relationship of the arc-related rocks with the GHS rocks from the northern India passive margin, and constrain the initiation and duration of the northward subduction within the eastern Neo-Tethys. Such discoveries will lead to a better understanding of how north-dipping subduction aided in the consumption of the Neo-Tethyan oceanic lithosphere, and potentially explain the anomalously fast convergence of India and Eurasia during the Late Cretaceous to Early Tertiary.

Data Availability Statement

Supporting information presented as part of this study is available from the in-text citation Z. Zhang (2023).

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