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Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction

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Abstract

The isotope geochronology of isochronously deposited Cambrian strata from different tectonostratigraphic zones of the Himalaya confirms new stratigraphic, sedimentological, and faunal evidence indicating that the Himalaya was a single continental margin prior to collision of India with Asia. Lesser, Greater, and Tethyan Himalaya represent proximal to distal parts of a passive continental margin that has been subsequently deformed during Cenozoic collision of India with Asia. Detrital zircon and neodymium isotopic data presented herein discount the prevailing myth that the Lesser Himalaya has a unique geochronologic and geochemical signature that is broadly applicable to modeling the uplift history of the Himalaya. The conclusion that all pre-Permian Lesser Himalaya strata lack young detrital zircons that are present in the Greater and Tethyan Himalaya underpins previous arguments that the Main Central Thrust forms a fundamental crustal boundary that separates the Indian craton from an accreted terrane to the north. The supposition that Himalayan lithotectonic zones differ in detrital zircon age populations has also been used to reconstruct the unroofing history of the Himalaya during foreland basin development in the Cenozoic. Our data conflict with the underlying assumptions implicit in these studies in that samples of similar depositional age from both the Lesser and Tethyan Himalaya contain detrital zircons with similar age spectra. Similarities between the Kathmandu Complex and the Tethyan Himalaya support stratigraphic continuity between the former and either age-equivalent Greater Himalayan protolith or the Tethyan. Assuming that the complex rooted along the Main Central Thrust, these strata would simply have escaped intense metamorphism during Cenozoic tectonism. Alternatively, the complex may represent a part of the Tethyan Himalaya that was emplaced during an early stage of movement along a south-directed thrust fault located near the present-day structural position of the South Tibetan Fault System.

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1. Introduction

The early geological history of the Himalayan region is recorded in two lithotectonic zones that are separated by a belt of high-grade metamorphic rocks, the Greater Himalaya (GH) (Fig. 1). To the south, the Lesser Himalaya (LH) contain a thick Precambrian to upper Lower Cambrian succession that is unconformably overlain by Permian and younger strata. These rocks occupy the footwall of the Main Central Thrust (MCT), which carries rocks of the GH southward. To the north of the GH, the South Tibetan Fault System juxtaposes Neoproterozoic to Eocene rocks of the Tethyan Himalaya (TH) against the northern margin of the GH. The original depositional relationships between these two sedimentary successions, and the protoliths of the intervening GH, are poorly understood, and this has hindered understanding of the geological evolution of the Himalayan region for more than a century [1].

Three models have been proposed to explain the stratigraphic differences between these three lithotectonic zones of the Himalaya (Fig. 2). In the 'continuous margin' model, all three zones represent different proximal-to-distal parts of an ancient passive margin of northern India [2–4]. The 'crystalline axis' model [5,6] portrays the TH and LH as depositional basins separated by a basement high represented by the GH. More recently, DeCelles et al. [7] proposed a third, 'accreted terrane', model in which the GH represents the basement of an exotic terrane that accreted to the northern Indian margin during the Late Cambrian–Early Ordovician, and that the TH sedimentary succession is an overlying cover sequence. Each of these models predicts a unique set of stratigraphic, biogeographic, and geochronologic patterns for the geologic record of the Himalayan region. Here we use a combined stratigraphic and geochronologic approach to test these models and create an integrated model of the paleogeographical relationship of the three lithotectonic zones, prior to Cenozoic thrusting associated with accretion of India to Asia.

The accreted terrane model [7] is based on published detrital zircon age spectra of the GH and TH that show a wide range of Precambrian to Late Cambrian zircons, in contrast to LH bedrock samples that contain zircons exclusively older than 1.6 Gyr. These data, combined with a similar distribution of Nd model ages for sedimentary rocks, suggested that the LH is, en masse, characterized by older detrital materials than the two northern lithotectonic zones [7,8]. Samples of Cenozoic syn-orogenic molasse and modern stream sediment from the LH have been interpreted based on this idea, i.e., younger 500–1400 Ma grains as having been derived solely from the GH or TH [9,10]. However, examination of the stratigraphic context of all detrital zircon samples and most samples analyzed for Nd isotopic composition from the LH indicates that they came from older, dominantly Mesoproterozoic rocks, not exposed in the TH. It is therefore not surprising that published data from the LH have markedly different detrital zircon and Nd model ages.

Old rocks, such as the Mesoproterozoic samples from the LH, would naturally be expected to have detrital zircon and Nd model ages that contrast with detrital zircon and Nd model ages of younger rocks. Strata that range up to Lower Cambrian in the LH could have been sources of zircons to Cenozoic molasse and modern stream sediment. In fact, these strata, and possibly even younger Paleozoic strata that could have been removed below a prominent Permian unconformity in the LH, could also be represented in such molasse as recycled grains from eroded Permian rocks. The difference in depositional age of samples from the LH and TH that were analyzed in previous studies weakens the basis of the accreted terrane model, which requires that differences in GH, TH and LH detrital zircon age spectra reflect different geographical sediment sources with distinct ages of bedrock or recycled sedimentary grains.

Our test of the accreted terrane model involves examination of detrital zircon and Nd model ages

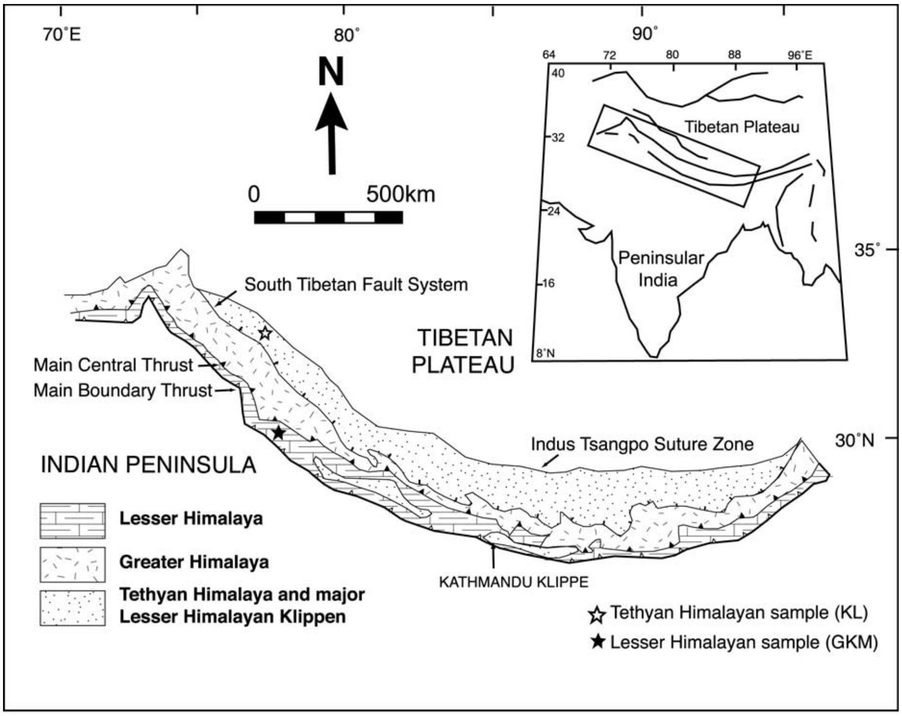

Fig. 1. Simplified lithotectonic zones of Himalaya in northern India and sample locations. The Lesser Himalayan (GKM) sample is the uppermost Tal formation at the Gopichand ka Mahal section: 30°10′33″N, 078°20′50″E. The Tethyan Himalayan (KL) sample is from the basal Kunzam La Formation in the Parahio Valley, Spiti: 32°02.685′;N, 077°54.491′E, 4008 m.

from rocks of the same age. Here we compare U–Pb detrital zircon data from LH and TH samples that can be shown, using independent fossil evidence, to be of similar depositional age. The comparison of isochronous samples complements new paleontological and sedimentological data and allows for clarification of the isotopic, faunal, and sedimentological relationships between the LH and TH zones. A Tethyan sample (KL) was collected near the base of the Kunzam La Formation from the Parahio Valley, Spiti region of Himachal Pradesh, India, along with trilobites and brachiopods that indicate an age close to the Early/Middle Cambrian boundary. A LH sample (GKM) was collected from member E of the Tal Group, at Gopichand ka Mahal, Uttranchal, India. Trilobites from a few meters below this upper unit (member D) of the Tal Group indicate a minimum age of latest Lower Cambrian [11]. Thus, the two samples have nearly identical depositional ages. Detrital zircons were separated from the two sandstone samples and dated with a SHRIMP ion microprobe at Australian National University (Fig. 3)[1].

2. Results

The TH sample (KL) contains zircons that range from earliest Archean (3455 ± 12 Ma) to latest Neoproterozoic (553 ± 3 Ma). Zircons from the LH (GKM) range from Archean (3526 ± 7 Ma) to Early Cambrian (525 ± 8 Ma). These spectra show similarity in both shape and overall range. Both of our samples show strong

[1] Zircon grain ages for these samples ($n = 60$, 67) are shown on relative probability plots (Fig. 3) along with summary detrital zircon age spectra for Cretaceous Tethyan strata, LH rocks, and the lower Nawakot Group of the LH [7]. Samples were prepared and analyzed using standard procedures outlined in [12,16].

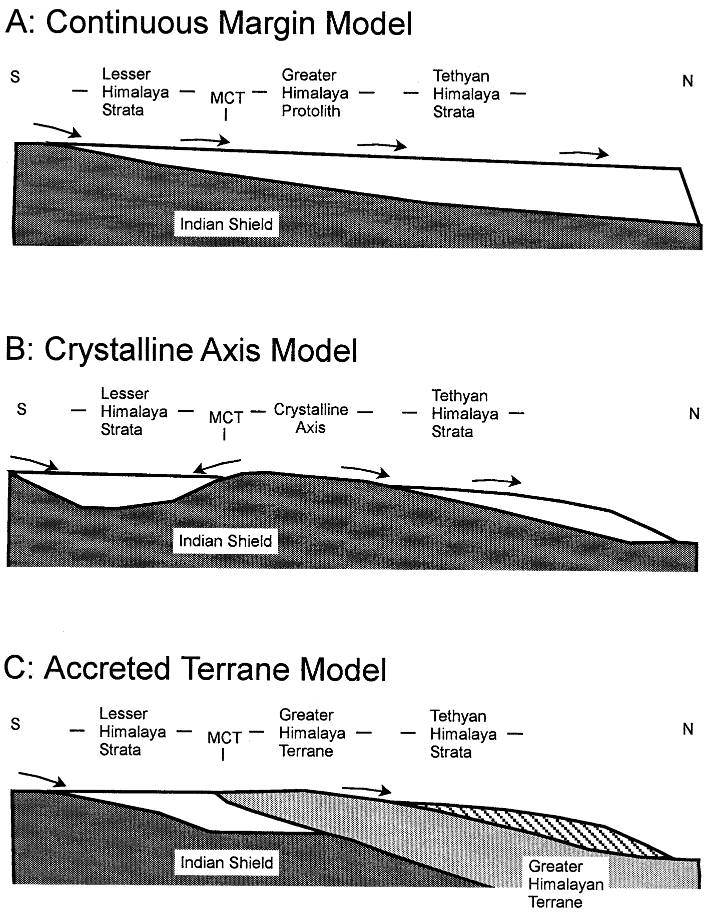

Fig. 2. Three models for the spatial and genetic relationship of the three northern lithotectonic zones of the Himalaya. (A) The continuous margin model postulates that prior to the Cambrian–Ordovician boundary event, the LH, GH and TH were all part of the northern passive margin of India. (B) The crystalline axis model suggests that a highland of high-grade metamorphic rock existed between the TH and LH prior to the Ordovician. (C) The accreted terrane model (after [7]) postulates that the GH sutured to India along the MCT during the Cambrian–Ordovician event and that the Tethyan Himalayan succession was deposited subsequently.

similarities to previously published spectra for the TH and GH zones (Fig. 3) [7]. However, there are several important differences. Firstly, both our samples lack young (∼500 Ma) grains, commonly attributed to Cambrian–Ordovician granites, because their depositional age pre-dates the formation of those granites. Secondly, previous results from the TH show few zircons >1.0 Ga. This may be due to the small number of analyses ($n = 19$, Fig. 3) or dilution by Paleozoic zircon, as our data show a large population of zircons older than 1.0 Ga (60% of sample). Thirdly, previous samples from the LH contain only zircons older than 1.6 Ga [7,13], whereas nearly 75% of the zircons from our LH sample are younger than this and range as young as 525 Ma. Thus, characterization of the LH as containing only >1.6 Ga zircons is a result of analyzing suites of zircons from older stratigraphic units.

The conclusion that all pre-Permian LH strata contain older detrital zircons than the GH and TH underpins previous arguments that the MCT forms a fundamental crustal boundary that separates the Indian craton from an accreted terrane

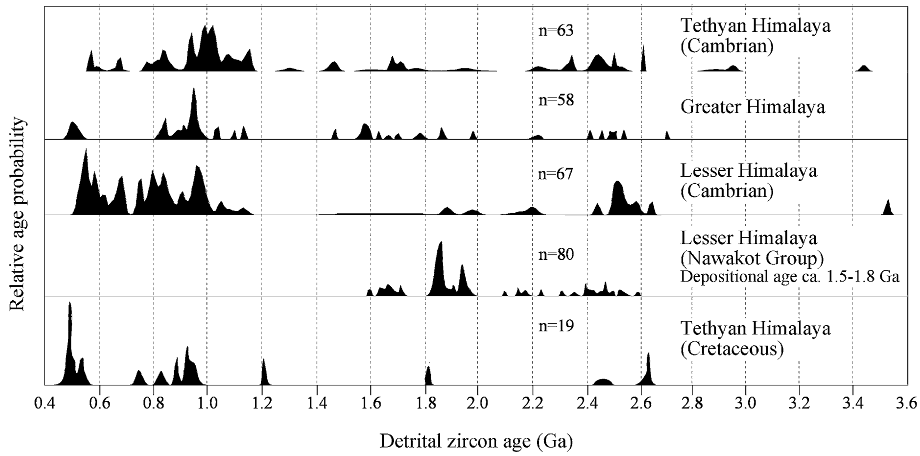

Fig. 3. Detrital zircon age spectra from samples taken in three northern lithotectonic zones of India. Cambrian samples from Tethyan (KL) and Lesser Himalayan (GKM) are from this study. Greater Himalayan and Mesoproterozoic Lower Nawakot Group data compiled by DeCelles et al. [7].

to the north. The supposition that Himalayan lithotectonic zones differ in detrital zircon age populations has also been used to reconstruct the unroofing history of the Himalaya during foreland basin development in the Cenozoic [9,10]. Our data conflict with the underlying assumptions implicit in these studies in that similarly aged samples from both the LH and TH contain detrital zircons with similar age spectra. Cambrian rocks of the LH and TH therefore appear to have been derived from similar sources, which contradicts the fundamental basis of the accreted terrane model [7]. Further, stratigraphic distributions of particular zircon age spectra within Himalayan foreland basin deposits lose much of their utility as a record of tectonic uplift of specific lithotectonic units in light of our data that indicate that each of the lithotectonic zones contain strata with similar age spectra. Although unroofing histories are based on multiple lines of evidence, they should be re-evaluated in light of the data presented herein.

Similar difficulties arise with interpretations of provenance based on initial Nd isotopic compositions and calculated model ages for sedimentary rocks (Fig. 4). Various authors have used Nd isotopic data to fingerprint lithotectonic zones [8–10,14,15] and characterize the affinity of tectonically isolated rock packages. This approach is based on the prevailing notion that all pre-Permian Lesser Himalayan rocks were derived from only Mesoproterozoic and older sources. However, a compilation of recently published data and our own new analysis[2] reveals that of the 63 samples analyzed from the LH, 52 are older than late Neoproterozoic and eight of these have isotope systematics that overlap samples from the GH and TH (Fig. 4). Eleven LH samples have depositional ages estimated to range from late Neoproterozoic to Early Cambrian based on stratigraphic criteria, and in every case their isotopic signature overlaps with GH and TH Nd data. Again, Cambrian rocks of the LH, GH and TH appear to have been derived from similar sources, rather than the separate sources required by the exotic terrane model for the GH.

In summary, similarity of the detrital zircon and Nd isotopic data (Figs. 3 and 4) eliminates the basis for reconstruction of the GH as an accreted tectonic terrane [7,8]. DeCelles et al.'s [7] claim, that the TH was deposited as a result of uplift related to the latest Cambrian–earliest

[2] We analyzed a shale sample from the upper Sankoli Formation of the Nigali Dhar Syncline, Lesser Himalaya collected at 30°38.566′N, 077°31.699′E, biostratigraphically dated as the earliest part of the late Early Cambrian. $\varepsilon_{Nd} = -17.65$; Model Age ($T_{Chur}$) = 1.682 Ga.

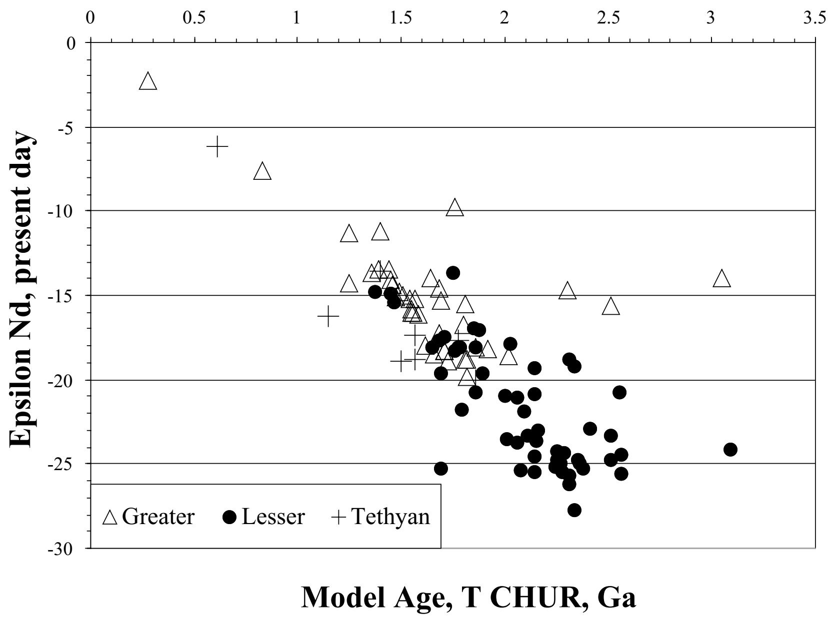

Fig. 4. ε_{Nd} (present day) and Nd model ages (T_{Chur}) for Lesser, Greater, and Tethyan Himalayan samples. Data compiled from 101 samples. One sample is new (see[2]), others are from the following sources: [8,15,30–35].

Ordovician accretion of the GH to India, was based largely on geologic relationships in Nepal, where the oldest dated rocks of the TH zone are Early Ordovician. However, although Ordovician TH strata were in fact deposited following tectonic uplift in much of the Himalaya, Indian Tethyan deposits contain thousands of meters of Neoproterozoic(?) through Middle Cambrian strata that pre-date this tectonic event [17]. A similar thickness of pre-Early Ordovician sedimentary rock also exists in Nepal and almost certainly pre-dates any Cambrian–Ordovician boundary event [18]. Furthermore, detrital zircon spectra from the GH range as young as 500 Ma, so the GH and TH were deposited contemporaneously, at least in part, and do not represent a simple basement-cover succession throughout the Himalaya. Older, more metamorphosed sedimentary or basement rocks would have underlain the Indian TH, but their nature is unknown. Detrital zircon analyses are thus consistent with a 'continuous margin' model [2–4] at least prior to Cambrian–Ordovician orogenesis. Minor differences in the detrital zircon spectra are noted, but expected due to variations associated with the difference in relative geographic position of the samples prior to Cenozoic deformation.

Additional support for a continuous margin is provided by sedimentological data. Paleocurrent data in the uppermost Lower Cambrian Tal Group of the LH show transport from south-southwest to north-northeast [19]. These are consistent with paleocurrent data we collected from the Lower and Middle Cambrian Kunzam La Formation in the Spiti region of the TH. This 1300 m thick deltaic unit was deposited in a variety of fluvial to shelf environments and likely overlaps in part in age with the uppermost member E of the Tal Group. Member E consists almost entirely of cross-bedded quartz-rich sandstone, much of which is of probable fluvial origin. The lithofacies are consistent with the LH representing a more proximal part of the northern Indian margin relative to the Tethyan. The TH has been thrust southward by 150–200 km or more along the MCT during Cenozoic orogenesis [20,21]. This displacement is partially balanced by several tens of kilometers of subsequent top-to-north normal fault displacement along the South Tibetan Fault System [1,22]. Palinspastic restoration of these faults is consistent with the Tethyan representing more distal deposits of the LH [3,4]. Paleontological data are also in agreement with the continuous margin model. Late Early Cambrian trilobite faunas from the LH and TH share species in common and both belong to the equatorial peri-Gondwanan faunal realm [11]. The above arguments, and the lack of evidence for suture zone rocks along the MCT, provide considerable support for the continuous margin model and are difficult to reconcile in either the crystalline axis and accreted terrane models.

The younger detrital zircon ages of the GH also rule out an earlier proposed 'crystalline axis' model [5,6], which portrays the TH and LH as depositional basins separated by a basement high represented by the GH. The close match of the spectra of GH samples to those of the other zones suggests that correlative sedimentary strata of the TH and LH may have formed the protolith of the GH. This view is complemented by similarities between the relic stratigraphy of the GH and the Neoproterozoic through Cambrian succession of the TH. The 'stratigraphy' of the GH [23] includes: (1) Formation I gneisses of siliciclastic metasedimentary origin; (2) Formation II calcareous gneisses and marbles; and (3) Formation III, with pelites and graywacke succeeded by coarse augen gneiss and a cap of metamorphosed limestone. Contacts between these units are gradational [23,24]. The siliciclastic to carbonate transition from Formations I to II may have parallels in the Cambrian stratigraphy of the Zanskar region of the TH [25], where a thick siliciclastic-dominated succession (Phe Formation) is overlain by a thick carbonate succession (Karsha Formation). The transition into mixed siliciclastic and carbonate deposits of Formation III is more difficult to interpret. Existing geochronologic data on Formation III [24,26] point to a Late Cambrian age, and thus indicate that its protolith may have been a volcano-sedimentary (?) correlative of the Cambrian Kargiakh Formation of the Zanskar region or even younger strata. Precise matching of particular units of sedimentary TH successions with units in the GH may never be possible, given the metamorphic grade of the latter, but the relationships proposed above are strong possibilities given the first-order similarities in age and present/protolith lithologies.

Rejection of the crystalline axis model does not rule out the possibility that during the Cambrian–Ordovician tectonic event uplift of strata south of the present position of the STDS took place or that such an area could have been a highland source of sediment for Ordovician molasse. In fact, paleocurrents in the Ordovician molasse deposits of northern India have paleocurrents that indicate transport to the north and northeast [27]. However, there is no strong evidence for a highland separating the LH and TH prior to that time.

Interpretation of sedimentary strata of the TH as the protolith of the GH is also consistent with recent work on the Kathmandu Complex or 'klippe' in the LH. The Kathmandu Complex has generally been reconstructed as a thrust slice of the MCT, although Hodges [1] noted the markedly lower metamorphic grade of lower Paleozoic strata of the complex relative to the GH. The lower metamorphic grade of these rocks has led to a long-standing debate regarding the origin of the complex. Recently, Johnson et al. [28] argued that the Kathmandu Complex is not a klippe and that it probably roots in the MCT. Johnson et al. [28] explain the metamorphic changes from the MCT to the Kathmandu Complex as reflecting the difference in the foreland position and structural level of the rocks prior to thrusting. If this is the case, then the lower Paleozoic sedimentary rocks within the Kathmandu Complex represent a relatively unmetamorphosed package of GH protolith, supporting the continuous margin model.

Although known geologic relationships support this interpretation, other aspects of the complex are also consistent with the possibility that it may have rooted along the South Tibetan Fault System as a remnant of early south-verging thrusting that pre-dated recent north-verging normal movement associated with gravitational collapse [29]. The metamorphic grade associated with the structurally lowest levels of the complex is similar to that found within the southernmost parts of the Tethyan zone adjacent to the GH and the South Tibetan Fault System. Additionally, relatively undeformed Silurian strata in the Himalaya are preserved only in the TH; they are absent in the LH, where Permian strata rest directly on the Lower Cambrian. Middle Cambrian to Lower Permian strata are also cut-out below a Permian unconformity south of the extension of the MCT (the P–K fault) in Pakistan, whereas to the north of the fault a full pre-Permian Tethyan succession exists [29]. Whether the Kathmandu Complex represents (1) a part of the GH that roots back to the MCT and escaped strong metamorphism, or (2) a part of the TH that moved along the STDS, remains an unresolved problem. If the former, this supports correlations between the TH and relic stratigraphy of the GH, i.e., that correlative strata of the TH were the GH protolith. However, if the complex roots back to the TH along the STDS, then thrusting along the South Tibetan Fault System would have extended far to the south, at least as far as the southernmost exposure of LH klippe. These hypotheses can be tested by further geochronologic and stratigraphic analyses focused on the uplift and syn-orogenic depositional history of the Himalaya.

Acknowledgements

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