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Age of initiation of collision between India and Asia: A review of stratigraphic data

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Abstract

The collision of India with Asia is perhaps the most profound tectonic event to have occurred in past 100 Ma. It is responsible for the uplift of the Himalayas and Tibetan Plateau and has been argued to have been responsible for geological, geochemical, and climatological consequences of global extent. Yet the age of initiation of this collision remains poorly constrained. The literature is replete with estimates that range from the Late Cretaceous (>65 Ma) to latest Eocene (<40 Ma) with little consensus in between. This paper reviews the available stratigraphic evidence from the Himalayan region, and concludes that only in the western Zanskar–Hazara region is the age well constrained as starting in the Late Ypresian ($\sim <52$ Ma). To the east only in the Malla Johar region of the Tethyan Himalayas have potentially syn-collisional sediments been recognized south of the Indus Yarlung Zangbo suture. However, here the correlation of the upper part of the Sangchamalla Flysch is contentious, with correlations ranging from Late Cretaceous to Middle Eocene (Lutetian). In the most eastern sections of Tertiary rocks thus far recognized within the Tethyan Himalayas north and east of Everest (Mount Qomolangma) normal, shallow shelf-type carbonates extend into the Lutetian, without evidence of a change in sedimentation to the top of the section, so the start of collision must be still younger. Along-strike of the Indus Yarlung Zangbo suture thick submarine delta-fan complexes derived from erosion of the Himalayan–Tibet system provide independent estimates that agree with a diachronous collision initiating in the late Ypresian in the west and progressing into and perhaps through the Lutetian in the east. The stratigraphic and magmatic history along the north side of the suture are compatible with such a diachronous history. This diachroneity has important implications for estimates of the accommodation of strain within this orogenic system.

Keywords: India; Asia; Himalayas; plate collision; chronostratigraphy

1. Introduction

The India–Asia collision is the archetypical continent–continent collision. The uplift of the Tibetan Plateau and resulting changes in the Earth's orography and consequent climate change are directly tied to this ongoing collisional event. Considerable attention continues to be focused on the history of this orogenic belt, and particularly on the processes associated with the uplift and exhumation of the Himalayas and development of the Tibetan Plateau. Given the enormous interest and importance it is perhaps surprising that the age of initiation of this collision, referring specifically to the time of elimi-

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nation of oceanic lithosphere between these continents, remains quite poorly constrained and has been subject to significantly varied interpretations [1]. Much of the discrepancy results from the different and generally indirect approaches that have been used to date the start of this collision. For example, terrestrial faunas of Cretaceous/Tertiary boundary age present in India are similar to coeval faunas of Asia and have been inferred to imply collision by 65 Ma [2,3]. At the other end of the spectrum, an apparent change in velocity of India with respect to Eurasia at about C13 (~ 33.0 Ma) [4] has been used to date the initiation of collision. This estimate has been updated by more recent analyses incorporating more tie points that place the change in velocity at C21 (~ 47.0 Ma) [5,6]. Others have pointed to the marked change in spreading direction within the Indian Ocean [5] between C20 (~ 43 Ma) and C19 (41.3 Ma) to date the collision at closer to 42 Ma. Several recent summaries simply quote times as somewhere between 55 and 40 Ma [7–9]. Obviously, more direct data are needed to delimit more narrowly the timing of the beginning of this collision. All ages referred to in the text use the Berggren et al. [10] time scale for consistency of correlation among the radiometric, biostratigraphic, and magnetic records, and thus older estimates based on changes in seafloor spreading have been revised to reflect this new time scale.

Collisions between an arc and passive continental margin are associated with marked changes in patterns of subsidence and sedimentation, particularly along the passive-type margin. Dating the onset of collision usually is straightforward, involving the dating of rapid subsidence associated with thrust-loading, followed by a change in provenance of sediments. Approximate ages and rates of shortening within the internal parts of orogens can be derived from the tectonic truncation of sedimentation by overthrust sheets. A younger bound on the age is

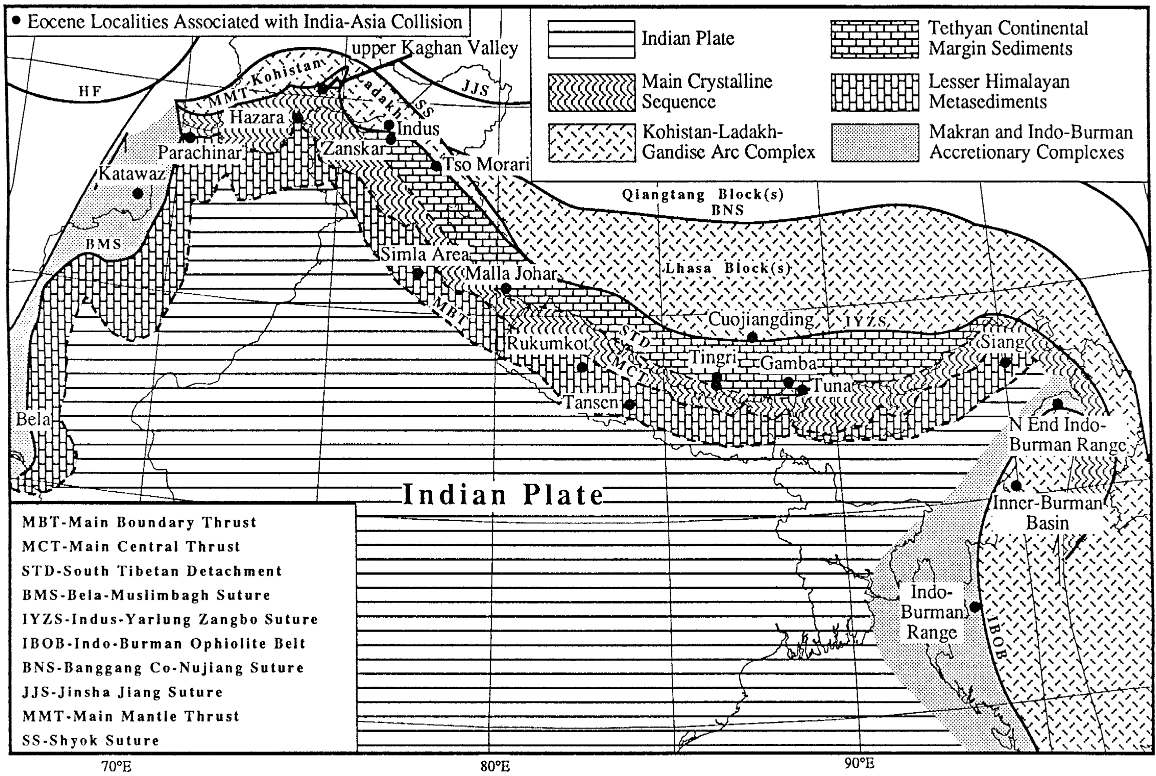

Fig. 1. Simplified map of the Himalayan region showing the main regional tectonic elements discussed in the text. ● = localities bearing on the age of India–Asia collision.

obtained by the age of unconformably overlying sediments. In the following, stratigraphic data from the Himalayas are reviewed to assess what is presently known about the age of initiation of the collision of India and Eurasia.

Much of the Himalaya Range has been mapped only in reconnaissance fashion, resulting in only relatively limited data directly constraining the age of collision. Below, the existing stratigraphic data from the region of the Indus–Yarlung Zangbo suture (IYZS) are reviewed to assess the constraints implied as to the timing of collision by indicating when there is a change in depositional character, for example, from shelf to foredeep basin with the arrival of allochthonous detrital materials, or by demonstrating that depositional style did not change, at least up to the age of the top of the preserved section, implying a still younger age of initiation of collision. Additional constraints may also be placed by the history of the fore-arc basin north of the suture, and by depositional histories of basins along depositional strike of the collision. Fig. 1 shows where data are available to place some limits on the timing of initiation of collision and some of these data are reviewed below and summarized in Fig. 2.

Before starting the review it is important to gain some perspective on the rates and length scales associated with the India–Asia convergence. During the interval prior to the end of C21 (46.3 Ma) the western and eastern tips of India were converging with Asia at a rate greater than 110 km/my and 120 km/my, which dropped abruptly to about 50 km/my and 68 km/my after C21 [5,6], respectively. Sections that contain strata through the lower Lutetian

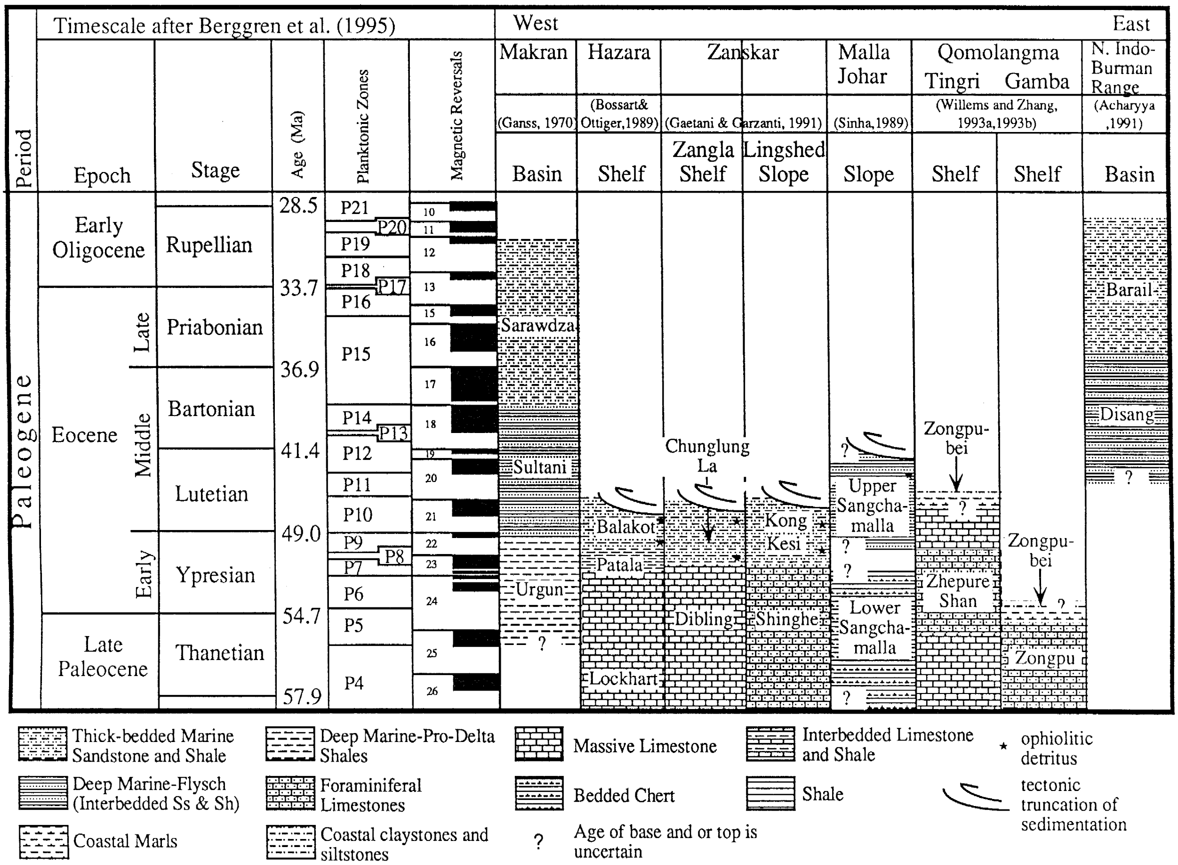

Fig. 2. Stratigraphic columns showing the correlation of units preserved south of the Indus–Yarlung Zangbo suture or in along-strike depositional basins. The location of each section is shown in Fig. 1.

on the passive margin shelf south of the suture were probably situated within a few kilometers of the shelf edge and thus only 1–3 Ma from arrival at the trench and hence would not contribute significantly to misdating the age of initiation of the collision. Thus a revision in the age of collision from around 50 Ma to 65 Ma would increase the amount of convergence between India and Asia by more than 1500 km.

2. Stratigraphically constrained timing south and along-strike of the IYZS

The Zanskar region (34.3°N, 76.5°E) (Fig. 1), in the western Himalaya, is characterized by a rich stratigraphic record [11,12] including a completely conformable Cretaceous to Tertiary succession. On the basis of this record Gaetani and Garzanti [11], and Garzanti et al. [12] demonstrate that collision-related deposition started here within the Ypresian (approximately zone P8) and that the Ladakh arc complex and the Spontang ophiolitic nappe were emplaced onto the Indian margin, tectonically truncating sedimentation in the early Lutetian (within P10). This is shown by the abrupt change in provenance during the Ypresian, marked by the arrival of northerly, ophiolite-derived debris in the Chulung La and Kesi Formations of P8 age. Assuming that emplacement of the Spontang and Ladakh ophiolitic-arc sequence dates initiation of the collision of India with Eurasia, then in the Zanskar region collision began in the Ypresian at about 50.7 Ma. Collision certainly could not have been older, as passive margin sedimentation is continuous below the middle Ypresian [11]. Support for a Ypresian collision in the west is provided by an essentially coeval change from shelf to foredeep basin sedimentation recorded by the transition from Late Thanetian Lockhart Limestone and early Ypresian Patala Formation shales into the flysch of the Balakot formation of Bossart and Ottiger [13] in the Hazara syntaxis (34.5°N, 73.5°E) (Fig. 1) [13]. Bossart and Ottiger [13], who have worked at the northern end of the syntaxis, have demonstrated that the unit they informally referred to as the Balakot formation ranges from late Ypresian to lower Lutetian age (upper P8 to P10). Like the Kesi, Kong and Chulung La, the Balakot formation also contains northerly, ophiolite-derived material in an apparently very thick (> 10 km) foredeep basin clastic wedge that prograded south across the Hazara syntaxis region. Note that the Hazara syntaxis lies due south of the Kohistan arc complex, which is the western continuation of the Ladakh arc complex.

Further support for a Ypresian age for the start of the collision in the west is provided by the progradation of sediments in the Katawaz Basin, the northern extension of the Makran accretionary complex in southeast Afghanistan (Figs. 1 and 2) [14]. Deposition of a thick sequence of clastics in this basin began with the Urgun, which is characterized by very thick pro-delta clays of Paleocene or Early Eocene age that pass upward into Middle Eocene rhythmic, delta-front sandstone–shale flysch (Sultani Formation); these in turn pass upward into delta-top sandstones of progressively more non-marine character of Late Eocene to Oligocene age (Sarawdza) [14]. This section is in excess of 8 km thick [15]. This southwesterly prograding deltaic complex, that was deposited on Jurassic–Cretaceous ocean floor tectonically attached to the Indian subcontinent [15], demonstrates that collision-related orography was being eroded in the vicinity of the Hindu Kush during the Ypresian and that this continued throughout the Eocene in southeastern Afghanistan. On a larger scale the continued southward progradation is shown by the later, Middle or Late Eocene through Oligocene influx of sediments farther south in Baluchistan, as recorded by the Khojak flysch [16].

Quite recently, Beck et al. [17] argued for a somewhat older age in the Parachinar area of the frontier region of northwest Pakistan, where an older unconformity with Thanetian strata of upper P5 and P6 age is developed on top of the Jurassic–Cretaceous Kahi Melange (Fig. 1). The Kahi Melange lies structurally below what Beck et al. [17] refer to as the Waziristan Igneous Complex, which they correlate to the Kohistan arc. The Kahi Melange and unconformable P5–P6 cover were, in turn, deformed together and unconformably overlain by P9 (late Ypresian) carbonates. Beck et al. [17] therefore place initial collision as pre-P5 and possibly as old as the Cretaceous/Tertiary boundary. Beck et al. [17] dismiss the Zanskar region, stating the data are 'ambiguous', primarily citing the tectonically oriented work of Searle [18] who had inferred a Late Cretaceous age for ophiolite obduction. Gaetani and Garzanti [11], and Garzanti et al. [12] specifically addressed Searle's [18] interpretation and showed that there was no change in sedimentology and provenance and therefore no evidence for a Late Cretaceous obduction event in the Zanskar area. They observed that passive margin shelf and slope sedimentation continue through P5 and up to within P8 in the Zanskar region without interruption, contrary to the expectations of Beck et al. [17]. There is, however, no reason to question the observations and inferences documented by Beck et al. [17]. Rather, it is important to recall that similar relationships, although considerably less well dated, are observed along the Bela–Muslimbagh–Khost suture (Fig. 1), which represents an obduction event of ophiolitic assemblages to as far south as the enormous Bela ophiolite [19] in southern Pakistan. Although there is ambiguity in the north where Beck et al. [17] have worked, there is no ambiguity at the latitude of Bela (26°N, 66.5°E) that collision here was not between the southern Trans-Himalayan margin of Asia and the northern passive margin of India, but rather reflects an intra-oceanic event independent of the India–Asia collision. The critical boundary to the west of the Khost suture is not the Kabul suture of Tapponnier et al. [15], but the Katawaz Basin. The Katawaz Basin is where Ganss' [14] work was done, and is the offset continuation of the Makran [20]. Subduction continued within the Katawaz Basin throughout the Eocene after obduction of the Khost ophiolites [15]. Tapponnier et al. [15] do not characterize it as a suture, presumably reflecting the absence of ophiolitic rocks within the basin, but it clearly operated as the plate boundary zone in this area through the Eocene. It is this additional subduction boundary that isolated this pre-P5 (pre-56 Ma) obduction event of Beck et al. [17] from the India–Asia collision proper. Thus their interpretation does not, in fact, directly and unambiguously date the beginning of the India–Asia collision. Once again it is important to emphasize that Beck et al. [17] have provided perhaps the best dating of this separate event, and thus neither their observations nor conclusions regarding the history of events in their area are in dispute, only their extension to the entire India–Asia collisional system.

It seems clear both from the Zanskar and Hazara regions, and as well from the Makran region, that collision-related sedimentation began in the early Eocene, within zone P8 (50.7 Ma) of the Ypresian. Foredeep sedimentation in both the Zanskar and Hazara basins was terminated in the Early Lutetian during zone P10, which lasted from about 49.0 to 45.7 Ma [10]. Thus the preserved duration of syn-collisional sedimentation in the Zanskar and Hazara regions is only between about 2 and 5 Ma. Farther west, along-strike of the orogen in the Makran region the very thick sediments of Eocene, through Oligocene and younger, demonstrate that sediment-producing orography was sufficient to supply a delta–submarine fan complex of the same order as the present Bengal fan to the east. This implies that uplift and erosional exhumation have been on-going throughout the duration of the collision, and are not more recent (Miocene and younger) manifestations of this collision.

Little data are available east of Zanskar until the Malla Johar region (Fig. 1), about 530 km to the east, near the intersection of the Nepal, India, and China borders (30.7°N, 80.2°E). Sinha [21] and Mehrotaha and Sinha [22] recently reinterpreted the age of the Sangchamalla flysch in this area. The Sangchamalla comprises graywackes, shales and radiolarian cherts subjacent to the Kiogar exotics of Permian, Triassic, Jurassic and Cretaceous carbonates that have been known since 1892 [23] and the Jungbwa ophiolitic nappes [24], derived from the Indus–Yarlung Zangbo suture zone to the north [21]. As in the Zanskar region, Late Cretaceous shelf sediments are conformably overlain by the Sangchamalla flysch demonstrating that this flysch is in situ relative to the underlying stratigraphy. The lower Sangchamalla shales are well dated as Late Cretaceous in age, in accord with Heim and Gansser [23], but the age of the upper, graywacke-bearing part is imprecisely dated at best. Mehrotra and Sinha [22] interpret the top part of the formation as Middle Eocene in age, based on dinoflagellates, radiolaria, and coccoliths. The age assignment of Mehrotra and Sinha [22] is, however, disputed by Jain and Garg [25] who claim that at least the dinoflagellate microfauna of Mehrotra and Sinha [22] is entirely of Late Cretaceous age. Mehrotra and Sinha [22] do not provide sufficient detail as to where in the section various fossils are derived to assess whether the Jain and Garg [25] re-interpretation raises questions as to the correlation of the entire section. The correlations of the radiolaria and coccoliths [21,22] still imply a Middle Eocene age. If the Mehrotra and Sinha [22] age is correct, the start of collision in this region is dated only to within the Middle Eocene (49 to 41.3 or perhaps 36.9 Ma). Clearly, more detailed collections and correlation of the upper Sangchamalla would be extremely helpful. Some support for a post-Ypresian time of collision in this more eastern region is, however, provided by the absence of any indication of syn-collisional sedimentation in the Lesser Himalaya to the south of the Main Central Thrust. Here, Batra [26], based on detailed analysis in the Simla area (centered around 31°N,76.9°E), describes the Ypresian to early or middle Lutetian Subathu Formation as consisting of shales and limestones that grade upward into regressive but biostratigraphically undated red sandstones. The total section attains a combined thickness of less than 150 m. This sequence, which is situated in a position tectonically equivalent to Balakot in the Hazara syntaxis, shows no evidence of collision prior to middle Lutetian (i.e. ~ 45 Ma). A correlative sequence of the Subathu is also seen farther east in the Rukumkot region, near Maina (29°N, 82.3°E) [27] and in the Tansen region (~ 27.9°N, 83.9°E). Here, the Eocene Bhainskati Formation is also about 150 m thick and characterized by brackish and shallow marine limestones and shales [28], also suggesting a post-Early Lutetian age of initiation of collision. The ~ 700 m thick fluvial Dumri Formation of Oligocene–Miocene age that disconformably overlies the Bhainskati marks the oldest preserved foreland basin sediments in this area.

Still farther to the east, Late Cretaceous to Eocene sediments are next described in the vicinity of Tingri (Xegar) (28.5°N, 86.5°E) on the northern slopes of Everest (Mt. Qomolangma), and then between Gamba and Tuna (28.1°N, 89.0°E) (Fig. 1) [29–34]. These are classic sections that have been known for nearly a century. In both the Gamba [31] and Tingri [32] sections fossiliferous Upper Cretaceous to Tertiary units are completely conformable. Willems and Zhang [31,32] have recently described these sections in detail and re-examined their biostratigraphic correlation. Their work forms the basis of the following discussion and columns in Fig. 2. In Gamba [31] the uppermost Cretaceous to Tertiary section begins with shallow marine Jidula Formation quartzose, ferruginous sandstones and limestones between 150 and 170 m thick, dated by algae and ostracods to the latest Maastrichtian to Middle Paleocene. These are overlain by the Middle Paleocene to Late Paleocene age Zongpu Formation, consisting of 200 m of predominantly of nummulitic limestones and marls. The Zongpu is conformably overlain by the Zongpubei Formation, which consists of about 160 m of greenish-gray marls overlain by red clay and siltstone with intercalations of fine sands. The Zongpubei is dated as straddling the Paleocene/Eocene boundary and extending into the lower Ypresian based on stratigraphic position. These are the highest level preserved in the Gamba section. To the west, at Zhepure Mountain, near Tingri [32], the uppermost Cretaceous to Tertiary sequence starts in a 225 m thick succession of pelagic marls with interbedded quartzose sandstones in the lower part, and mixed carbonate and siliciclastics in the upper part. These belong to the Zhepure Shanpo Formation that extends from the Middle Maastrichtian to Early Paleocene. The Zhepure Shanpo Formation is overlain by 97 m of calcareous and glauconitic sandstones belonging to the Early Paleocene Jidula Formation. These are, in turn, overlain by the Early Paleocene to Middle Eocene Zhepure Shan Formation, consisting of between 400 and 440 m of dolomites and dolomitic limestones overlain by mostly massive limestones above. The base of the unit is dated as Danian, while to the top is dated as Lutetian [32] (p. 43). The highest known sediments preserved in this region are coastal to lagoonal [33], greenish-gray marls overlain by red clay and siltstone with intercalations of fine sands lithologically correlated with the Zongpubei Formation. Here, the Zongpubei is dated as Lutetian or younger, based on its stratigraphic position above the Lutetian Zhepure Shan Formation. The new stratigraphic work [31–33] addresses a dispute as to the youngest age of the highest units in this region. Blondeau et al. [35] dated this sequence as no younger than late Ypresian, whereas Wen [30] and Hao and Wan [34] interpret the fossil evidence in terms of a Lutetian to perhaps Early Bartonian age, with the recent work favoring the younger interpretation.

The Tingri section, which contains the youngest unequivocally dated marine sediments in the Everest region provides the best constraint on the maximum age of collision in the central Himalayan segment. The close proximity (~ 65 km present distance) of this region to the Indus–Yarlung Zangbo suture argues that collision did not affect this area until after deposition of the Zhepure Shan Formation, and probably after the Zongpubei Formation. This places collision as starting sometime within the Lutetian or perhaps even more recent time.

Unfortunately, Early Tertiary rocks have not been mapped farther east than Tuna, at least immediately to the south of the Indus–Yarlung Zangbo suture and north of the Main Central Thrust [36]. Hence, no other data are available to constrain the time of collision farther to the east within the suture zone itself. Paleocene–Early Eocene nummulitic limestones, overlain by undated clastics, from the Siang district (28.1°N, 95.3°E) of Arunachal Pradesh some 670 km farther east, equivalent to the Subathu, have been described [37] but these provide little information to constrain the timing of collision in this region.

Still farther east and south around the eastern syntaxis, however, data are available within the along-strike equivalent of the Indus Yarlung Zangbo suture in northern Burma and Nagaland, India (Figs. 1 and 2). Here, the Naga Hills–Indoburman Range ophiolite belt marks the western boundary of a sequence of Albian to Recent sediments and volcanics that reside in a fore-arc position immediately east of the ophiolites. To the west of the ophiolites are Late Cretaceous and younger rocks that comprise a west-vergent accretionary wedge of flysch and lesser melange [38,39]. Late Cretaceous to Early Eocene rocks in this belt are *Globotruncana*-bearing limestones and shales that are disposed both as a broader belt and also as olistolithic components of the melange [38] comparable with equivalent age sediments preserved east of the Naga Hill–Indoburman Range ophiolites [40]. The Late Cretaceous to Early Eocene limestone–shale dominated sediments are juxtaposed tectonically with flyschoid shales and sandstones of the several kilometer thick Disang Formation. The Disang grades upward into progressively more arenaceous sediments of the Barail Group. The Disang and Barail are important as they were deposited east of the point of collision between the Indian subcontinent and Asia, and thus record sediments transported eastwards along-strike of the orogen [41,42], just as the Urgun, Sultani, and Sarawdza sequence in eastern Afghanistan were deposited to the west of the Indian subcontinent. The Disang does not contain abundant fossils and its stratigraphic base is nowhere observed, hence its age range is not well determined; quoted ages of its base range from Late Cretaceous [38] to Middle Eocene [43,44]. The oldest fossils from the matrix of the Disang are of Middle Eocene age [38] with the overlying Barail dating from late Middle Eocene or Late Eocene to Oligocene age [38]. Thus syn-orogenic sedimentation to the east of India does not appear to have commenced until probably Middle and perhaps late Middle to Late Eocene.

In summary, with the exception of the data from the Zanskar, Hazara and northern Makran region, it is not possible to establish with any precision when collision commenced farther east. Given the existing data, it is only possible to say that sedimentation of shelf-type extended into and perhaps through the Lutetian without evidence of collision. This would imply perhaps limited diachroneity of suturing, but the data are insufficient to constrain how much. If correlations of the uppermost rocks of Tingri, the Zongpubei, as Lutetian or possibly younger [30,32,33] are correct, then collision could be rather markedly diachronous, perhaps as much as the entire Lutetian (i.e. ~ 7.7 m.y.). This would accord with the apparently late onset of significant along-strike sediment transport into the Naga Hills–Indoburman Range area to the east. The absence of any late Ypresian or early to middle Lutetian clastics in this region comparable to those filling the Makran would be surprising if collision everywhere along the suture began in the Ypresian or even earlier, given that the eastern end of India was moving about 1.5 times faster than western end, reflecting its more distal position relative to the pole of rotation.

3. Stratigraphic data from north of the IYZS

The region of Tibet to the north of the Indus–Yarlung suture is characterized by an areally extensive volcano-plutonic complex (Kohistan–Ladakh–Gandise belt) to the south of which are ophiolitic rocks that mark the surface juncture of the suture. At various places between the ophiolites and volcano-plutonic complex, Cretaceous to Tertiary sedimentary basins are preserved that are generally inferred to have developed as fore-arc basins. The stratigraphic record of these basins should also reflect the interaction of the Eurasian margin with the northern margin of India and thus can also add to this discussion.

In the west, the Indus Group clastics represent a fore-arc basin assemblage developed on top of the Spontang and equivalent ophiolitic basement to the Ladakh Arc [45]. This fore-arc basin evolved from at least the late Albian to early Eocene [45]. Strata of the Indus clastics lap unconformably onto the plutonic core of the Ladakh batholith along the northern margin of the basin. The section is more complete farther to the south, with numerous intervals of interbedded limestone. Marine sediments persist into the Early Eocene and include nummulitic limestones interbedded with shales and siltstones. Unfortunately, no details are provided as to which nummulites are present, or of a more precise correlation of these sediments. The marine Urucha and Gonmaru Formations of Early Eocene age are overlain by terrestrial, alluvial fan (Hemis Conglomerate and Nurla Formation) and lacustrine sediments (Nimu Formation), but these are not dated, and are simply referred to as post-Early Eocene [45]. Garzanti and Van Haver [45] interpret the Hemis and Nurla as recording the final collision of Ladakh with India. The collision post-dates the nummulitic limestones and, by inference, is post-early Eocene. This suggests a date of younger than 49 Ma for the collision, but how much younger is not specified. This is consistent with data from the Zanskar stratigraphy immediately to the south, in that both the Kesi and Chulung La flysch sequences extend into the Lutetian before being tectonically truncated by the overthrusting of the Spontang and Ladakh thrust sheets. The Balakot formation in the Hazara syntaxis similarly extends upward into the Lutetian [13].

Eocene marine strata of the Cuojiangding Group are preserved to the east along the suture and overlie the Xigaze ophiolite and the Xigaze Group. The stratigraphy appears very similar to that described by Garzanti and Van Haver [45] for the Indus group, starting in interbedded carbonates, clastics and shales, grading up-section into progressively more clastic-dominated fan sediments, with interbedded limestones, followed by shales and limestone lenses and finally at the top into unfossiliferous, coarse clastics. This assemblages has been interpreted as recording various facies of a submarine, delta-fan complex [46]. The Cuojiangding contains fossils that range from Paleocene into the Early Eocene [46]. Unfortunately, the uppermost clastic unit of the Cuojiangding Group is unfossiliferous.

Once again, there is a significant geographic gap between approximately 89°E and the Nagaland–Indoburman region starting at approximately 94°E (Fig. 1). The Naga Hills–Indoburman ophiolites of Maastrichtian age marked the western boundary of the Inner Burman Basin, and were obducted by the Middle Eocene, as demonstrated by the unconformable overlap of terrestrial to shallow marine Phokphur Formation [38,39]. The Inner Burman Basin represents the eastward continuation of the fore-arc basin. The basement to the Inner Burman Basin is locally exposed, as in the Mount Victoria region. Here Albian to Recent sediments rest unconformably on Triassic, *Halobia*-bearing sandstones, shales and nodular limestones [40,43,47] that, in turn, overlie low grade schists, marbles, and granite gneiss referred to as the Kanpetlet Schists (see [43,47]) and/or Naga Metamorphics [40,48] of undetermined, but pre-Carnian age. The late Early and Late Cretaceous to Early Eocene sediments exposed along the eastern margin of Mount Victoria are characterized by significant amounts of carbonates, including *Globotruncana*-limestones, suggesting deposition beyond the influence of significant terrestrial sources and in relatively deep water [43]. During the Eocene the supply of erosion products from uplifted areas increased, and very thick (>5 km) mainly sandy and argillaceous sediments accumulated in the shelf area of the Inner Burman Basin [43]. In the late Middle and early Upper Eocene, conglomeratic layers of reworked older rocks and shaley red beds (in the Pondaung Sandstone) point to local continental erosion and redeposition in areas at the west edge of the central and northern Inner Burman Tertiary Basin. This may suggest that significant thicknesses of Disang and Barail sediments were being accreted resulting in uplift of the trenchward edge of the Inner Burman Basin. Uplift apparently occurred diachronously, commencing in the north and proceeding southwards to the central parts of the Indo–Burman ranges [43]. During the Late Eocene the supply of sediments may have outweighed the rate of subsidence in near-shore areas of the shelf in central and northern Burma. Thick and regionally extensive, generally marine, Late Eocene to Pliocene sediments occur throughout the central and southern Inner Burman Basin, demonstrating that the region as whole was not affected by the collision-related shortening until the Miocene or later, contrary to predictions of Tapponnier et al. [2,49].

4. Age of early metamorphism and granites

The recently recognized high eclogites in the Tso Morari region [50] and upper Kaghan valley [51,52] and nearby early syn-metamorphic granites [53,54] provide additional constraints on the age of collision. Phase equilibrium studies of the upper Kaghan valley eclogites yield pressures of 1.5 ± 0.3 GPa and temperatures of $650° \pm 50°$C [55]. Isotopic studies of the upper Kaghan valley eclogites indicates that they derived from basalts equivalent to the Panjal Traps [52] and were metamorphosed to eclogite facies at 49 ± 6 Ma [51]. Zircon dating of very early granites coeval with the earliest recognized deformation and metamorphism at between 49 and 47 Ma [53,54] are indistinguishable from age of the eclogites. Thus, the initiation of the collision must pre-date these ages. The convergence rate between India and Asia at the longitude of the Zanskar shelf prior to C21n (46.3 Ma) was more than 10 cm/yr [6]. As the maximum depth of subduction thus far recognized is about 60 km, it would have only taken the Indian crust between 1 and 2.5 m.y. to reach 60 km for slab dips between 30° and 15°. If Indian crust started entering the subduction zone at about 49 Ma, correlative with the age of termination of the foreland basin sequences of both Zanskar and Hazara, then the ages of the eclogites and granites are in accord with a late Ypresian age of initiation of collision. The age of eclogite facies metamorphism in the Kaghan valley and early granites therefore do not require an older age of collision.

Fig. 2 summarizes the existing timing relationships discussed above. Given this data there appears to be an eastward younging of the start of collision from ~52 Ma in the west to perhaps as young as about 41 Ma in the east. Thus the estimate of ~55 Ma for collision by [56], based on paleomagnetic results in northern Pakistan, are supported by the existing stratigraphic relations. Arguments based on the termination of the arc-related magmatism (e.g. [7,9,57]), at approximately 42 Ma are also supported by these data, as most of the younger arc-related plutons that have been dated lie in the vicinity of Lhasa, where the start of collision perhaps occurred closer to 42 Ma ago. It should be pointed out that this pattern conforms well with the general configuration of the northern margin of India, at least as judged by the geometry of the Indus–Yarlung Zangbo suture (Fig. 1). The western promontory of Kashmir and northern Pakistan collided earliest, the northwest–southeast striking segment collided diachronously next, followed apparently nearly synchronously by the east–west striking segment east of Tingri. This suggests that the pre-collisional geometry of this margin at least approximately mimicked the shape of the Indus–Yarlung Zangbo suture.

5. Implications

As has been well restated by both Butler [1] and Beck et al. [17], the India–Asia collision has had profound effects on not just local and regional geology but global geology, and perhaps global climate and ocean chemistry. Establishing as precisely as possible the age at which collision started at various places along this margin is critical to assessing the history of this impact. Knowing the age of collision allows us to understand, for example, the role of increased buoyancy of Indian crust on the global plate motions, rather than to infer the age of collision from the presumption that the observed changes directly reflect this event. In addition, several attempts have been made at assessing the mass-balance within this collisional system (e.g. [6,58]) in the hopes of quantifying the various modes of accommodation of strain. Richter et al. [6] described the mass-balance as functions of 4 main components of mass expressed in terms of volume, including: (1) the volume of crust before collision; (2) the present volume of crust within the Himalayan–Tibet system; (3) the volume removed by erosion; and (4) the volume of crust extruded or that escaped from the system (see, e.g., [49]). Estimates of the present volume of crust within the Himalayan–Tibet system can be derived from the topography (see [58]) and estimates of the volume removed by erosion can be derived from isopachs of major sedimentary accumulations derived from the erosion of Himalaya–Tibet. Present estimates suggest that about 1.5×10^8 km^3 of continental crust presently resides within Himalaya–Tibet [6]. Similarly, the mass of eroded material residing in the various sedimentary basins of the Indian Ocean, and Makran and Indo–Burman accretionary complexes amounts to about 0.4×10^8 km^3 of rock [6]. An estimate of the volume of extruded crust is then the difference between the initial volume and the present and eroded volumes

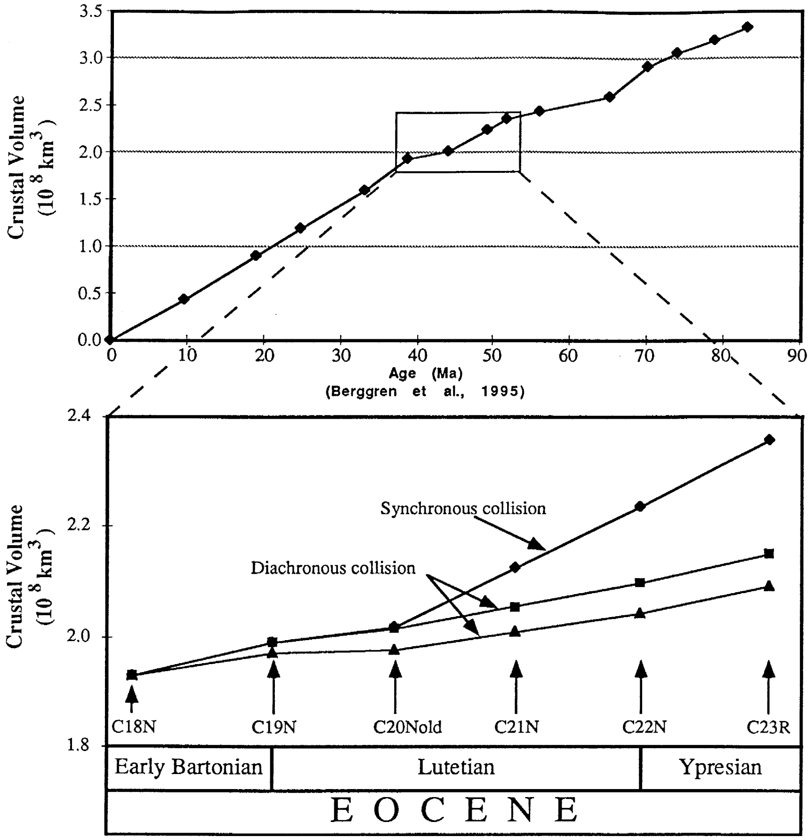

Fig. 3. Graph showing the volume of crust needed to reside within the collisional system for various assumptions as to the age and diachroneity of collision. Volume is computed from the area swept out by India's motion relative to Asia through time and an average crustal thickness of 35 km. Volume is chosen over area as it is essentially a conserved quantity. The upper graph shows that, were collision to have been synchronous along the entire length of the IYZS, the volume of crust within the system would lie along this upper curve, with the actual volume depending upon the exact age of collision. The lower graph shows a more detailed view, with the upper line in the lower graph corresponding to the line in the upper graph. The lower two curves show the best estimate (with squares) and minimum (with triangles) volumes given existing data, constraining the age of collision along the length of the margin. The lower curve accepts the stratigraphically determined age of collision in the Balakot and Zanskar segment, and assumes that initiation of collision was diachronous along the segment from Zanskar to Malla Johar and synchronous from there eastwards by C18N, or within the Early Bartonian, based on the Wen [29] correlation of the Upper Zhepure Group. The middle curve is similar to the lower curve except that it assumes initiation of collision extends eastwards of Malla Johar in the Middle Lutetian at C20Nold.

mentioned above [6]. The initial volume of crust can only be indirectly estimated by knowing when collision began, and using plate reconstructions to determine the position of India relative to Asia. If collision has just begun then continental crust must extend across the domain between India and Asia and hence the pre-collisional area of crust is determined. The volume of that crust is then derived by multiplying this area and an estimate of its average thickness. Although some have questioned our knowledge of the pre-collisional thickness, which obviously has some uncertainty, the main component that contributes to the uncertainty is the age of initiation of collision. Fig. 3 shows the dependence of crustal volume (assuming a 35 km average thickness) on age of initiation of collision. The upper figure in Fig. 3 shows that, were collision to have begun between 70 and 65 Ma [2,3] the pre-collisional crustal volume would have been between 2.7 and 3.0×10^8 km^3, or about twice the present remaining crustal volume of Himalaya–Tibet. Further, syn-collisional intra-continental crustal shortening in the Pamir region would be essentially 4200 km for collision starting at 65 Ma as opposed to about 2350 km for collision starting at the base of the Lutetian, which is approximately the age of tectonic truncation of sections in the Zanskar and Hazara regions. The equivalent numbers for the eastern syntaxial region are 5400 km and 3350 km, to as little as about 2800 km, if collision were to have started as late as the end of the Lutetian. The lower figure in Fig. 3 shows the dependence of crustal volume on various assumptions as to the age and diachroneity of initiation of collision. Given the above estimates of volumes, extrusion of crust could account for between about 15% of the total strain accommodation for synchronous collision starting at C21 (47 MA) to about 5% for the most diachronous history compatible with the existing data. Any additional constraint, particularly even one tie point for the age of initiation of collision in the eastern syntaxial region could dramatically improve our assessment of the magnitudes of shortening that need to be accommodated within the Himalayan–Tibetan system and, hence, the mass-balance of system. This would reduce the uncertainty of this component of the analysis and allow a more confident assessment of the relative contributions of crustal shortening and escape.

6. Conclusions

A review of the stratigraphic data bearing on the age of initiation of collision between India and Asia shows that it is only well constrained in the Zanskar–Hazara region, where it dates from the late Ypresian. The Eocene stratigraphy of the Katawaz Basin support the interpretation derived from the Zanskar–Hazara region. The data for regions along the suture to the east are compatible with diachroneity of collision, but do not fully constrain its magnitude. The initiation of coarser clastic deposition in the Indo–Burman Ranges and Inner Burman Basin are supportive of a later, Lutetian age of collision in the east. Together, these put bounds on the contribution of extrusion of crust at between about 5% and 15% of the total strain. ***[RV]***

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